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Optimizing the Portuguese wildfire fuel reduction program

Highlights

- We modeled spatially optimized fuel management scenarios
- The treatments targeted ignition frequency, large fires, and building exposure
- Substantial trade-offs were observed among the three treatment objectives
- The results downscale national policy objectives to site-specific treatments

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In brief

European countries that are beginning to grapple with climate-driven extreme wildfire events can utilize the reported methodology to systematically optimize the implementation of fuel management initiatives rather than rely on traditional *ad hoc*, local prioritization. Future work with scenario optimization models can provide insights on leveraging both traditional fuel management and land use change to build sustainable, fire-resilient landscapes in the Mediterranean region.

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Optimizing the Portuguese wildfire fuel reduction program

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SCIENCE FOR SOCIETY As European countries begin to grapple with an increasing frequency of extreme wildfire events, there is a broad consensus that a paradigm shift is needed to focus on managing wildland fuels rather than responding with additional investments in fire suppression. Multiple countries in the Mediterreanean basin and elsewhere have launched new national strategies aimed at reducing fuels on highly flammable peri-urban landscapes. The success of these policies may well hinge on how strategic, top-down policy goals are correctly interpreted in the field to prioritize fuel management in high-risk areas. In this study, we employed a scenario planning model to optimize the implementation of a national fuel management plan in Portugal and to understand tradeoffs among specific risk reduction objectives. The methods and modeling can be extended beyond fuel reduction programs to design longer term, optimized land use strategies that can potentially improve fire resiliency and reduce future fire suppression costs under a changing climate.

SUMMARY

The escalating wildfire problem in Portugal motivated policymakers to develop a wildfire management plan that calls for rural fuel reduction throughout the country. The plan specifies fuel treatments on 250,000–300,000 ha per year over 10 years. Spatial priorities for treatments were delegated to regional and municipal entities. We use a scenario optimization model to allocate and map fuel treatment projects using three hazard metrics (ignition probability, building exposure to wildfire, and potential large fires). The results reveal sharp decision trade-offs among the three priorities within many municipalities. Allocating a proportion of treatments to all municipalities rather than focusing on those with the highest hazard significantly reduces treatment efficiency. European countries that are grappling with climate-driven extreme wildfire events can utilize this methodology to systematically optimize the implementation of new wildfire policies, rather than rely on local, *ad hoc* prioritization of fuel management investments to achieve fire policy goals.

INTRODUCTION

Alarming trends in wildfire activity around the globe have motivated many new national policy initiatives to expand fire prevention and protection efforts. The upward trend in extreme fire events is expected to worsen, as climate drivers of wildfire activity continue to intensify over time at global scales.[1,2] In Europe, a recent study reported that 50% of Europe is expected to experience at least a 2-fold increase in the probability of extreme events and an extension of the fire season by at least 5 days by the end of the century.[3] Northern regions, including the UK and Scandinavia, that historically have not experienced extreme fire events are expected to face a new reality when climate change creates novel fire regimes over large forest landscapes.[4] In the Mediterranean basin, fire is already challenging government institutions and emergency response systems, and studies predict even more significant impacts on extreme fires than elsewhere.[3,5,6] Preparing for future fires will need a paradigm shift from the current reliance on wildfire suppression as the primary defense strategy rather than a balanced approach that makes significant investments in prevention and landscape fuels reduction,[7–9] especially under future climate.[5] Wildfire governance systems are beginning to recognize the need for large-scale changes in wildfire management strategies, especially in Portugal, where new programs have been initiated that emphasize a wide range of fuel reduction techniques (pastoral grazing, mechanical treatments, and under burning) matched to specific vegetation types[10] and, in some cases, implemented in concert with land use change for longer-term resolution to the fire problem.

While multiple countries in the Mediterranean region and elsewhere have launched new or expanded existing national strategies aimed at reducing landscape fuels,[10,11] implementation is carried out under highly diverse legal and administrative frameworks with the one common theme that prioritization is decentralized to local administrative bodies and guided only by broad policy guidelines.[11] For instance, in Greece, the AntiNero program[12] paved the way for the allocation of 72 million euros to Forest Service field units to design and implement fuel reduction treatments aiming at reducing wildfire risk. In Spain and Italy, investments are being made of similar magnitude, with regional entities tasked with developing local strategies and prioritizing treatments and other fire prevention measures.[11] In France, fire management is guided by the national Vulcain program, with the actual implementation governed by administrative districts.[11,13] In Portugal, which has the highest incidence of wildfires in the Mediterranean region[14] (4.6 million ha burned between 1984 and 2021), a new 10-year fuel management plan[10] developed by the Rural Fire Management Agency (AGIF) has been funded with 200 million Euros. Like elsewhere, identifying on-the-ground priorities among and within municipalities has been delegated to regional and local entities.

Decentralized planning and prioritization are a common theme in natural hazard mitigation and ecological restoration programs.[15] Goals are broadly defined in umbrella strategies that conform to science and legal frameworks that translate policy to priorities and practice on the ground.[10] However, this approach burdens policy translation among the administrative hierarchies in decentralized organizations, and the original policy intent can unravel as directives and goals are filtered through multiple administrative tiers of governance and local stakeholder groups engaged in the prioritization process.[15,16] To our knowledge, newer wildfire policy initiatives in the EU[17] were developed without spatial scenario analyses to prioritize areas for hazard reduction and identify investment trade-offs and benefits in terms of reduced wildfire risk.[18] Thus, the long-term success of new fire risk mitigation strategies in the diverse Mediterranean governance systems[7,11] and elsewhere[8] may well hinge on how strategic, top-down policy goals are interpreted and used for prioritizing local fuel management projects. This downscaling process in the Mediterranean region is further complicated by the fact that 80%–98% of rural wildlands consist of small privately owned[19] abandoned parcels that form contiguous areas of high biomass.[7,20–23] Linkages across scales are needed in these diverse landscapes to help achieve spatially coordinated changes in fuels at the scale of large fires.[15,24,25]

In the US, advances in fuels mapping, fire simulation, and scenario modeling set the stage for the development of a national scale, spatially explicit plan that calls for treating 20 million hectares that pose the bulk of the wildfire risk on US National Forests to adjacent developed areas.[8] The underlying scenario was modeled to specifically bridge scales between a national policy to targeted investment to the ground and scheduled treatments over 10 years focused on potential sources of wildfire risk to communities at a resolution of 100-acre parcels.[8,26] The analyses identified 8 million hectares of national forest parcels (on top of current levels of treatment) and 12 million hectares of non-national forest land that was responsible for 80% of the exposure to communities based on simulation modeling.[26] The existence of the detailed plan and highly focused treatment objective directly contributed to substantial new funding to the Forest Service from the Bipartisan Infrastructure Law passed by the US Congress in 2021. The linking of the funding to the plan demonstrated the value of using scenario models to identify spatially explicit priorities and linking them directly to umbrella policies, including future wildfire impacts to the plan.

Extending this high-resolution scenario analysis at national scales in other fire-prone countries presents many challenges and has heretofore not been attempted. In this study, we address this gap by modeling scenarios to downscale the newer national fuel management in Portugal. The Portuguese National Fire Plan[10,27] includes a 10-year fuel management plan to reduce national wildfire risk and was adopted following the catastrophic 2017 fire season and aims at (1) reducing the cumulative burned area by around half, (2) reducing the percentage of fires larger than 500 ha by around half, and (3) substantially reducing the loss of lives in rural fires. To achieve these and related objectives, the plan proposes the expansion of fuel management programs targeting rural areas and includes a 3,538 km long fuel break network (FBN)[10] in concert with an additional two million hectares of landscape treatments. However, precisely where and when treatments are implemented and organized into effective landscape projects has been largely left up to local fire managers within the 278 municipalities, potentially disconnecting the priorities in the national plan. We used the scenario planning model ForSys[28] to identify optimal national fuel treatment scenarios using predicted and historical fire impact metrics as objectives for the three goals of the Portuguese plan (number of large fires, ignitions, and exposure to buildings). Single and multi-objective scenarios were modeled to understand if the goals were competitive or complementary within each region, meaning that prioritizing one goal would allocate treatments in areas that would address the other two goals. We then analyzed the effect of pro-rating treatment area to all 278 municipalities proportional to the overall risk in the region (equity scenario) versus treating areas with the highest risk without considering regional boundaries (efficiency scenario). The results demonstrated the application of spatial optimization to downscale national wildfire policy to local fuel management projects and identify decision trade-offs among different policy goals at the municipality scale. Application of the methods in other fire-prone countries can help government institutions develop strategic visions required to foster collective landowner action at the scale required to significantly change large fire behavior.

RESULTS

Area required to treat 80% of hazard metrics

Example spatially optimized project areas are shown for two municipalities in Figure 1. Prioritizing projects based on the three different hazard metrics resulted in substantially different spatial distribution of treatments in both municipalities, meaning

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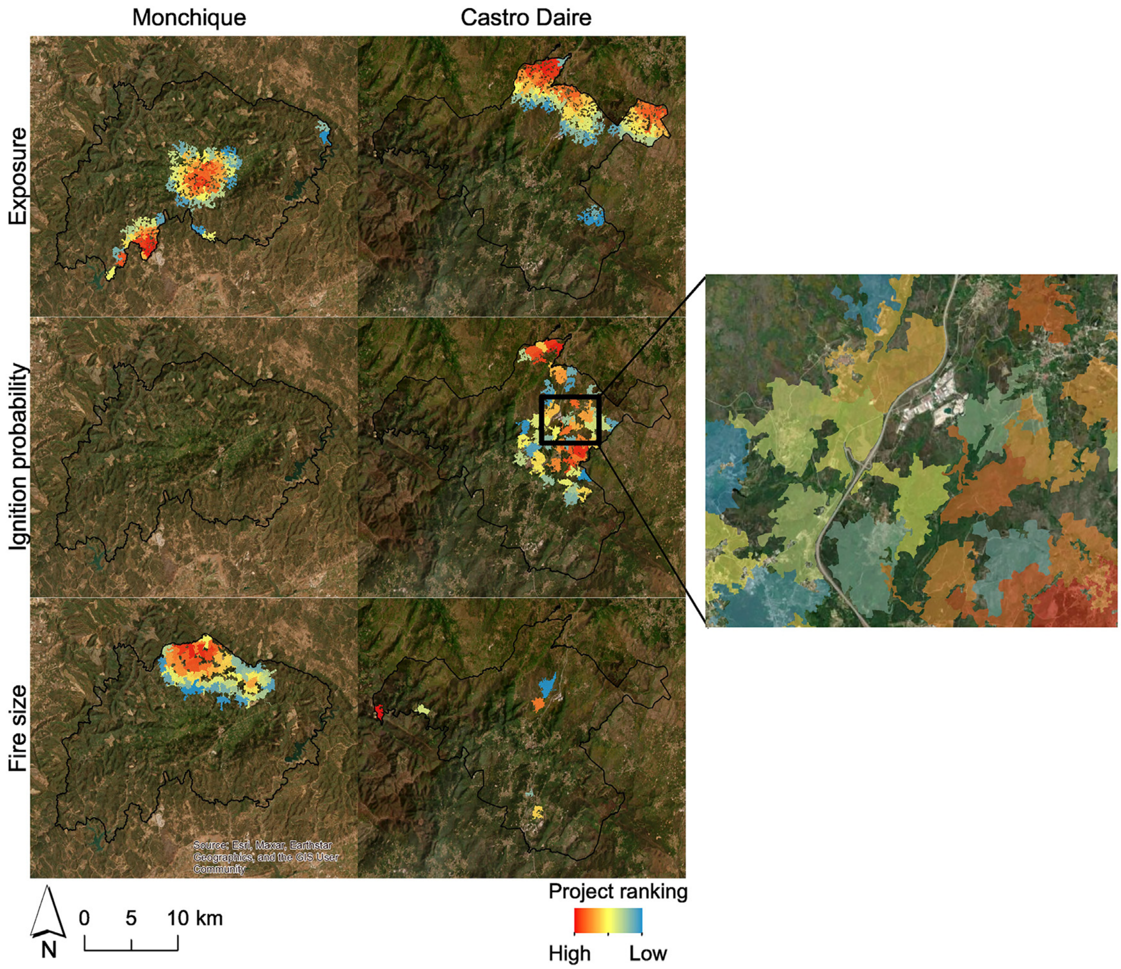

Figure 1. Map showing 50 of the highest-ranked project areas for each of the three hazard metrics in two example municipalities
Monchique (right) is located in southern Portugal in the Algarve region, and Castro Daire is in northern Portugal in the Norte region. Project areas were spatially optimized within each municipality based on the level of hazard in the individual parcels. The number of projects allocated to each municipality varied according to the two different scenarios (efficiency versus equity; see Figure 8). Warmer colors represent higher priority projects for each municipality, i.e., higher levels of predicted hazard. Right panel shows finer-scale map of the individual project areas for Castro Daire when prioritized based on ignition probability.

that optimum treatment solutions are specific to each hazard metric. Note that under the efficiency scenario where the prioritization of treatments was based on hazard at the national scale, there are municipalities that were not allocated any projects (Figure 1).

A substantially different treatment area was required to treat the parcels that were responsible for 80% of each hazard metric. The fire size hazard metric required treatments in 12.5% of mainland Portugal, versus 21.6% and 28.8% for the building exposure and ignition probability, respectively. The total area of treatments under the efficiency scenario also varied substantially among regions (Figure 2). In general, variation in the total area treated in each region reflected the proportion treated, meaning that the density of the treatment target was more or less uniform among the regions. For instance, the Centro region required the largest treatment in both proportion and total area (Figure 2). The one exception to this pattern was the Algarve region, where a larger proportion of the region required treatment for all three hazard metrics, indicating a more diffuse spatial distribution of the treatment target. The allocation of treatments under the efficiency scenario also resulted in wide variation in the percentage of each municipality treated because treatments were allocated according to the level of hazard across Portugal, versus equal area allocation under the equity scenario (Figure 3). Many municipalities with low hazard were allocated relatively few projects under the efficiency scenario.

We found that about 25% of the treatment area required to target 80% of the fire size hazard metric was located inside protected areas, particularly in the Alentejo, Algarve, and Centro regions. As expected, the treatment area was substantially lower in protected areas under the building exposure and ignition reduction scenario since these are usually areas with low population density (Figure S1).

10-year treatment scenario

Comparison of the equity versus efficiency scenarios showed that allocating resources to conduct fuel management in all

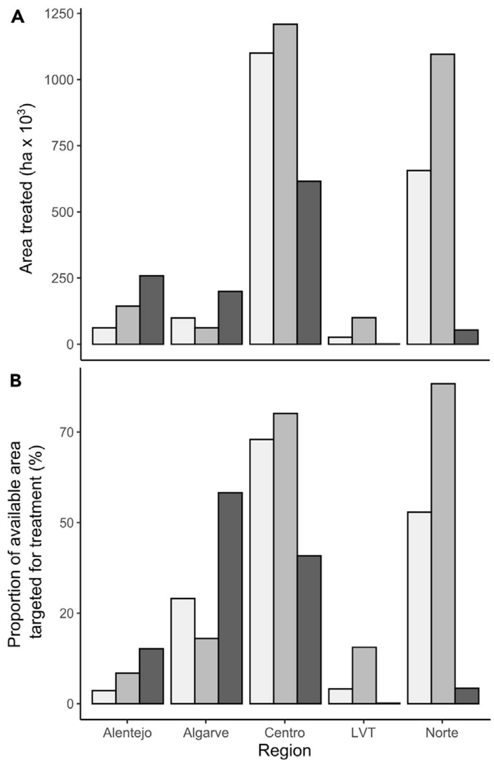

Figure 2. Area and proportional area requiring treatment to address 80% of the total hazard in Portugal by region and hazard metric for the efficiency scenario

(A) Total area requiring treatment to target 80% of the hazard.

(B) The proportion of the total area requiring treatment in (A). Graphs show the variability among regions in the total area and proportion of area targeted for treatment for each of the three hazard metrics.

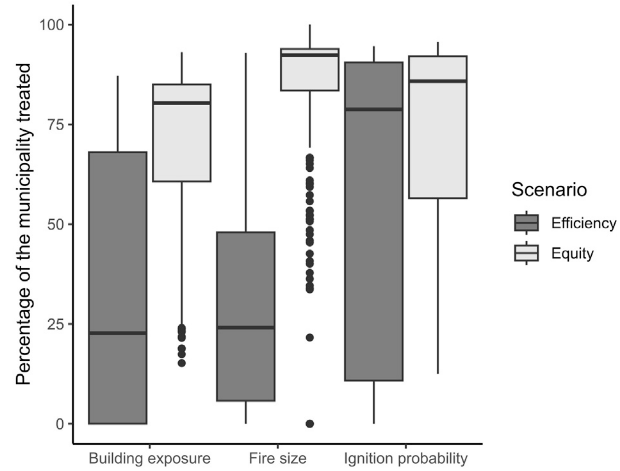

Figure 3. Box plot of the percentage of each municipality treated under the efficiency and equity scenario for the three hazard metrics

The scenarios treated the lands responsible for 80% of the national hazard for each metric. Graph shows that the total area treated per municipality varied widely for the efficiency scenario when treatments were allocated according to national hazard, versus equal allocation under the equity scenario. Many municipalities with relatively low but locally significant hazard were not allocated fuel management projects under the efficiency scenario.

municipalities versus only those with the highest exposure led to decreased performance as measured by the rate of hazard treated over time. The cumulative hazard metric treated over the hypothetical 10-year plan for the three metrics (Figure 4) showed rapid and a nonlinear rate of progress for the efficiency scenario, versus a linear increase for the equity scenario. The large fire hazard metric achieved the 80% level after 5 years for the efficiency scenario and 6 years for the equity scenario with the fixed treatment area of 250,000 ha per year. The other two treatment hazard metrics (ignition probability and building exposure) achieved an 80% level in 8 and 10 years under the efficiency scenario, respectively. By contrast, the 80% treatment target was not met over 10 years of treatments in the equity scenario. As expected, the random scenario where project areas were prioritized at random from the efficiency scenario (versus prioritized based on a hazard metric) underperformed the other scenarios in terms of treating areas with high level of hazard (Figure 4).

Trade-offs and optimality

In terms of trade-offs among the three national hazard metrics, we found that the exposure and ignition probability hazard metrics were complementary compared with fire size, reflecting the fact that ignitions tend to occur close to urban settlements where the potential for building exposure is the highest (Figure 5). Prioritizing fire size had more pronounced trade-offs with the other hazard metrics, presumably because potential fire size is larger outside of developed areas where ignition probability is lower. This is in agreement with the characterization of wildfire macro-regimes described in the methods section.[29] The pattern of Pareto frontiers did not significantly change among the scenarios, but there were substantial differences among the regions. For instance, the Algarve region Pareto frontier showed that treating areas with high potential for large fires was generally not compatible with the other two hazard metrics. This finding was the result of large fires driving the exposure in some regions (Centro and Algarve) and smaller fires elsewhere (e.g., Norte). This latter finding means that reducing the number of ignitions brings little benefit in terms of decreasing the area burned in the Norte region.

Regional patterns in priorities

Priority treatment areas shifted over time among the regions in the hypothetical implementation plan under the efficiency scenario (Figures 6 and 7). For instance, for a large fire hazard (Figure 6A), treatments were allocated in the early years of implementation primarily in the Centro region, followed by Alentejo and Algarve. Later in the plan, the allocation shifted to include treatments in lower priority areas in Norte, with concomitant decreases in treatments to Alentejo and Algarve. Prioritizing building exposure (Figure 6B) led to most of the treatments being allocated to the Centro region in the early years of the plan, followed by region Norte. For ignition probability (Figure 6C), Norte received the most treated area in the first year of implementation (ca. 85% of the total), with the rest 15% being shared between

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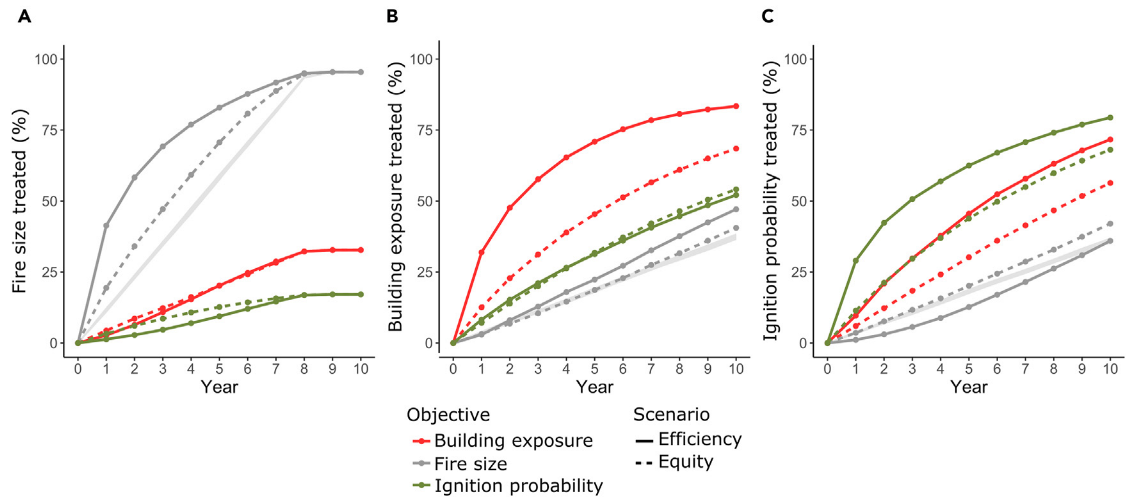

Figure 4. Rate of progress toward treating the three hazard metrics for a 10-year implementation period (250,000 ha per year) where project areas are spatially optimized and then prioritized for implementation based on the level of hazard

(A–C) (A) Large fires, (B) building exposure, and (C) ignition probability. Solid lines show the results for the efficiency scenario, where parcels are selected for projects based only on hazard, and dashed lines show the equity scenario, where all municipalities are allocated treatments proportional to their total hazard. Also shown is the random variant of the efficiency scenario where projects were selected for implementation at random.

regions Lisboa and Centro. It is noteworthy that prioritizing large fire hazards resulted in Alentejo treatments being mostly allocated to the municipalities of Chamusca, Nisa, and Gavião (close to the border with Centro) and Almodôvar and Odemira (close to the border with Algarve). By contrast, prioritizing ignition probability allocated treatments close to the more densely populated regions of Lisboa or Norte (municipalities of Torres Vedras, Sobral de Monte Agraço, Lourinhã, Arruda dos Vinhos, Alenquer, Bombarral, and Estarreja and Albergaria-a-Velha), respectively.

DISCUSSION

This study provides a rare example of using scenario planning to link goals in a national fuel management initiative to optimize fuel treatment projects and link priorities to the ground. The study was motivated by an ambitious government plan[10] to tackle the increasing frequency of severe fire seasons in Portugal and similar initiatives in neighboring countries. The analytical approach differed significantly from the prior national-scale modeling in the US[8] in that (1) projects were spatially optimized, (2) multiple management objectives and trade-offs were analyzed, (3) multiple allocation strategies were used to understand how including all municipalities in the fuel treatment program (equity scenario) affected the efficiency of treating wildfire hazard metrics (efficiency scenario), and (4) a random variant of the efficiency scenario demonstrated the overall value of prioritizing risk and hazard reduction investments. A logical follow-up study would test the effect of the treatment scenarios on fire behavior and building exposure[30] using the fire simulation system developed in our prior work.[31]

Although the AGIF plan heavily relies on fuel reduction treatments to accomplish broad social and ecological objectives, spatially explicit priorities at the scale of fuel treatment projects were not included in the plan, which is a common approach to national fire management strategies elsewhere.[7,11] The premise for this study is that investments need to be optimized to efficiently achieve intended outcomes, and decision trade-offs understood before strategies are implemented. Moreover, cross-scale linkages are needed to ensure that top-down policy goals are translated to local priorities for local stakeholders. Without this knowledge, investments are bound to be inefficient, and without linkages, it will be difficult to track progress toward achieving the original policy intent as treatment goals are filtered through multiple administrative tiers of governance. The scenario analysis we conducted was made possible by multiple advances in fire simulation modeling, vegetation,[32] fuel model mapping,[33] and spatial optimization heuristics in the ForSys model.[26] The resulting plan includes treatment schedules that can be used by AGIF and the Portuguese Forest Service to communicate and justify funding needs for fire management and sustain a national-scale strategic dialogue with policymakers. The model framework has a wider application to accelerate planning, prioritization, and implementation of risk and hazard reduction investment in other countries to ensure intended outcomes are achieved.[34,35]

The modeled scenarios specifically examined a common problem in national-scale hazard mitigation programs concerning the equity of investment allocation among and within finer-scale jurisdictions at which projects are planned and treatments are implemented. Two divergent scenarios were analyzed, one that allocated treatment area across Portugal solely based on hazard metrics (efficiency scenario) and the other pro-rating treatments to each of the 278 municipalities based on levels of hazard within them (equity scenario). We found that the efficiency scenario was, in fact, more effective at targeting treatments to areas with high levels of the hazard metrics, especially in the early years of the simulated 10-year plan where the treatment response was predicted to be nonlinear. Response in the

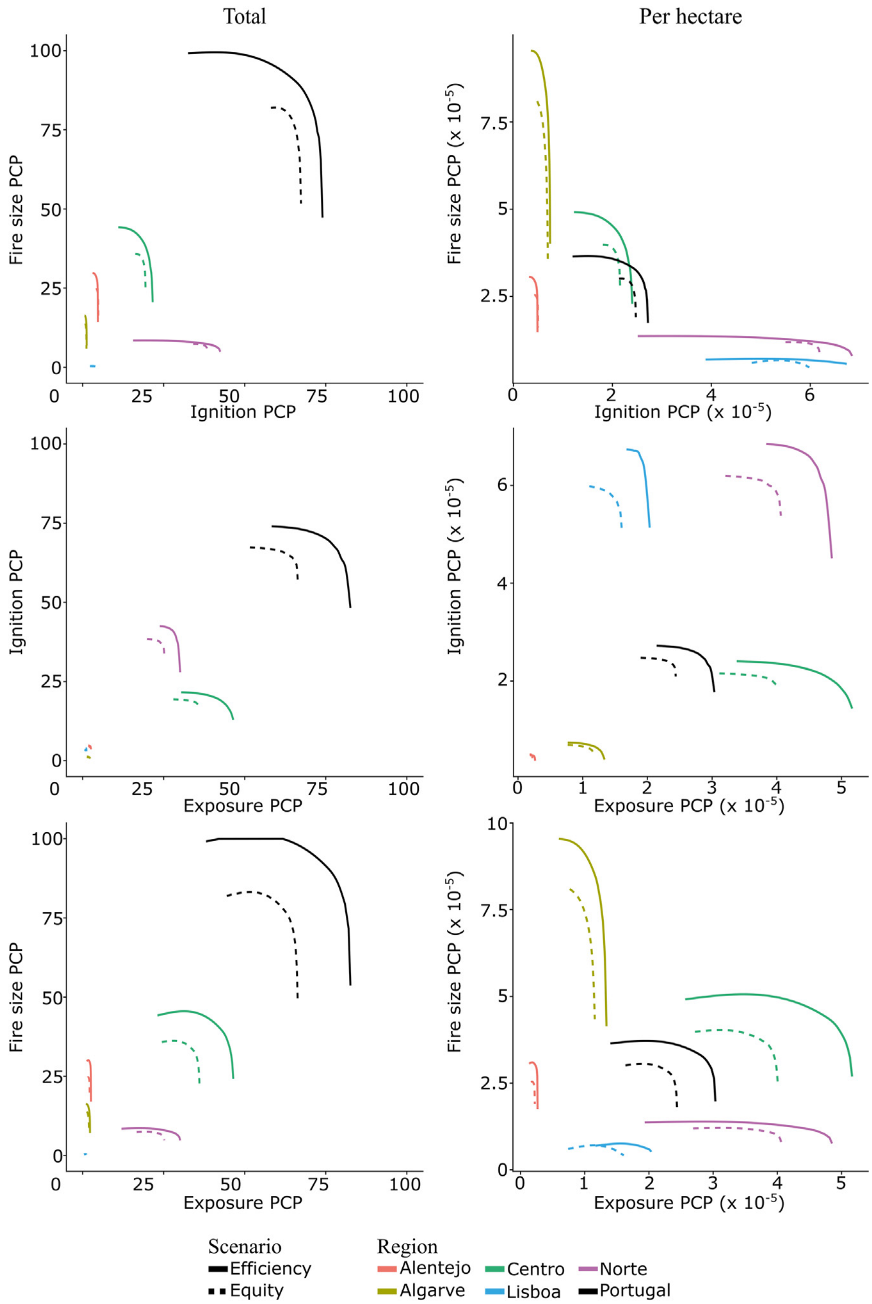

Figure 5. Pareto frontiers for the five regions and the cumulative for Portugal under the Efficieny and equity scenarios as derived from modeling alternative weight combinations among the three hazard metrics

Graph shows that trade-offs among treating one hazard metric versus another varies by region. The PCP is the percent of the total treatable objective for each of the metric, meaning that if a scenario treated every parcel with a non-zero objective, the PCP would be 100%.

equity scenario in terms of hazard treated was more or less linear, with more projects and treatments required to meet objectives, especially for building exposure and ignition probability. Conversely, treatments in the efficiency scenario all reached 80% of the target between 5 and 10 years into the plan, depending on the response metric. The objective of reducing large fires was achieved in a shorter time frame under both implementation scenarios, partly because treatments were targeted to a relatively small area where predicted fire size was >500 ha. A variant of the efficiency scenario where projects were prioritized in a random order (versus based on hazard metrics) underperformed both the equity and efficiency scenarios, demonstrating the value of prioritization as part of implementing fuel management programs. Overall, these results show that careful prioritization that targets high-hazard areas makes an important difference in the outcomes in terms of addressing the national policy goals.

We observed scale-dependent trade-offs among the three national objectives (reducing ignitions, reducing the number of large fires [≥500 ha], and reducing building exposure), suggesting that it would be difficult to create a perfectly balanced strategy among the three national objectives in most but not all regions and municipalities. Management trade-offs were more substantial when treatments were focused on reducing the number of large fires versus treating for the other two objectives. Trade-offs like those identified here create challenges for planners to balance competing objectives and are widely observed, especially evident between ecological and social goals.[36–39]

Many spatial patterns emerged from the analysis in terms of the efficiency at which treatments targeted the different hazard metrics and shifting regional priorities as treatments were implemented over the assumed 10-year plan. For instance, treating areas that generated large fires required allocating treatments to all regions, except Lisboa, where most of the landscape is urban and the area of unburnable fuels is relatively high. In general, large fires are observed in all regions of Portugal, although fine-scale drivers have been identified, such as the location of the ignition and distance to settlements and roads.[40–42] By contrast, treating the area responsible for building exposure and ignition probability was most efficiently targeted to the Centro and Norte regions. Targeting ignitions in general led to treating areas with a small fire size and low probability of large fires in accordance with previous studies that found that the probability of an

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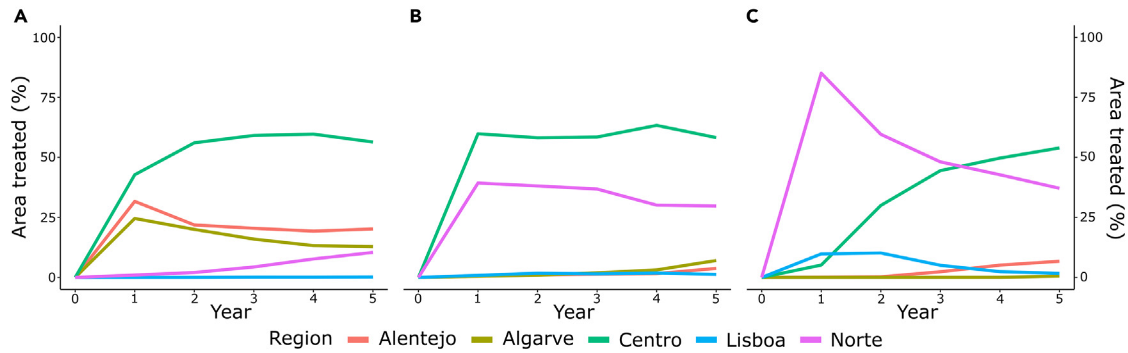

Figure 6. Regional differences in the area treated over the first 5 years of a hypothetical 10-year plan that treats 250,000 ha per year for the three different hazard priorities under the efficiency scenario

(A–C) (A) Large fires, (B) building exposure, and (C) ignition probability. Area treated is percent of the total available per region. Graph shows significant shifting of treatment priorities among regions over time when prioritization ignores municipality boundaries and projects are allocated based on the level of hazard across Portugal.

ignition resulting in a large burned area is inversely related to population density.[42] For all hazard metrics, the allocation of treatments to the different regions shifted over the 10-year implementation period as high-hazard areas were treated (Figure 6).

Currently, Portugal is relying on two distinct fuel treatment strategies in the 10-year national program.[10,27] Strategic landscape treatments are being implemented to reduce fuel continuity that contributes to large and extreme fire events.[10] Concurrently, a nationwide FBN is being implemented with the primary objective of facilitating fire control. The network initially consisted of a total of about 3,000 km (37,500 ha), primarily along mountain ridges.[43,44] These linear fuel breaks can facilitate wildfire suppression operations as well as for controlled burning operations to maintain treated areas.[45] The effectiveness of the national FBN in Portugal and similar networks elsewhere has been questioned by researchers in a number of studies,[46,47] mostly because suppression crews do not always choose to use them or are not available to prevent fire from jumping the treated area. Using fire simulation methods Aparício et al.[47] studied intersections between the FBN and simulated fire perimeters in Portugal to assess the potential reduction in burned area and building exposure and found that predicted burn-over percentage was significant and highly variable among segments in response to estimated fire intensity, and thus landscape-scale treatments are also needed to meet national wildfire management targets. There is widespread interest in spatially coordinating both types of treatment strategies,[48] and new optimization formulations are needed to measure the dual benefits of the respective approaches and determine where there are strong co-dependencies and trade-offs between one or the other strategy. For instance, landscape treatments are needed where FBNs are most likely to fail or do not provide other longer-term management objectives, including the expanded use of prescribed fire[25,49,50] and pastoral burning.[51] The difficulty in formulating this optimal allocation problem arises from the fact that the divergent spatial strategies do not have many performance metrics in common that can be used in a weighted optimization approach to assess the relative benefits.

It is important to recognize that the fuel treatment plan and other mitigation measures being implemented by AGIF[10] and modeled in this study provide only a short-term solution to the longer-term wildfire problem in Portugal since maintaining the post-treatment fuel loadings will require costly retreatments every 5–10 years.[25,52,53] Long-term solutions will require significant change in land use and associated rural economy to transform current vegetation into sustainable and resilient low-fire hazard landscapes.[45,54–56] Much of the current fire regime in Portugal has been attributed to afforestation and agricultural abandonment, resulting in the expansion of shrublands and commercial forests that increased fuel continuity and flammability.[23] Reversing this trend will require expanding specific land uses and management practices, including pyro-silviculture in the forestlands,[57] livestock grazing in the shrublands,[58] pastoral burning,[51] and cultivation of crops with low flammability.[59] Designing these landscapes at the municipality scale could take advantage of a planning framework described in this study to find cost-efficient land use scenarios to re-fragment landscape patterns of fuels.[60,61] Scenarios could incorporate ecological suitability, fire resiliency, and landowner management preferences to reflect a wider range of factors that affect the potential for change on specific land types[49,55,62]). The cost of agricultural and other subsidies required to support economically marginal land uses over time could then be compared with the current suppression cost, which ranges around 130 to 220 million euros per year (2018–2023) in Portugal. For instance, in the modeling study by Lecina-Diaz et al.[63] it was found that expanding crop cultivation and planting fire-resistant tree species resulted in a significant reduction in suppression expenditures and losses to timber resources. However, their study area included only a small sample of the many vegetation types in Portugal, and the methodology needs to be expanded to evaluate many other changes in land use and associated cultivation systems before robust guidelines for land use transitions can become part of new fire management policies. Future work with scenario optimization models could potentially provide insights on leveraging both traditional fuel management and land use change to build sustainable, fire-resilient landscapes in the Mediterranean region.

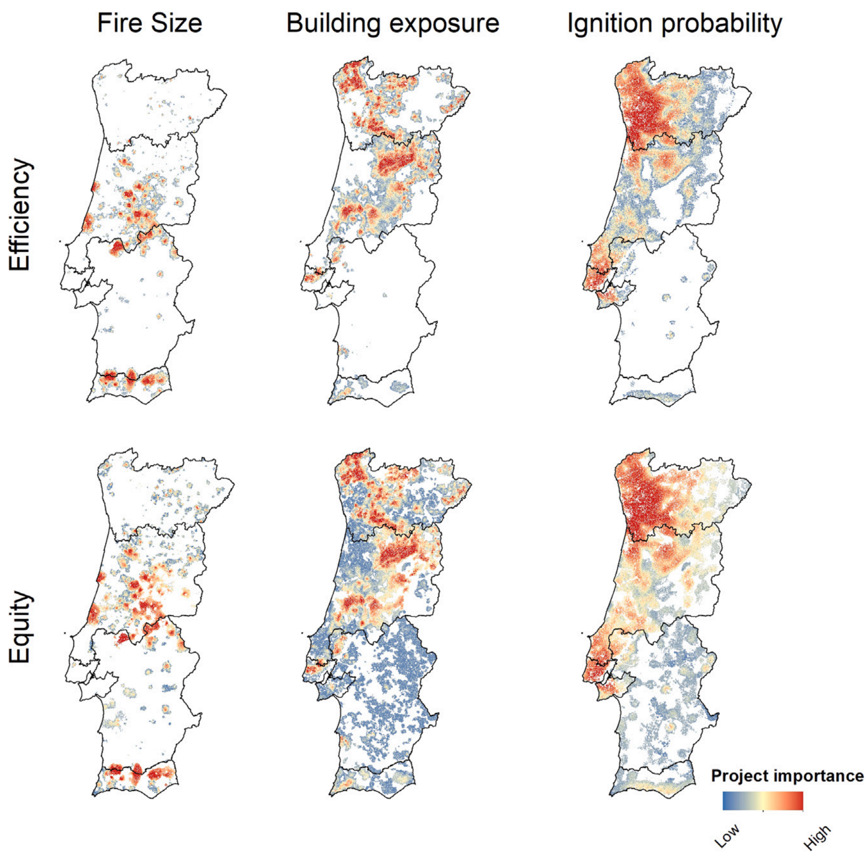

Figure 7. Project priorities for the efficiency and equity scenarios for the three hazard metrics selected for analysis

Note the wider spatial distribution of projects under the equity scenario where projects are allocated equally among the municipalities. Both scenarios treat the land base responsible for 80% of the total hazard. Priorities were rendered using equal interval categories and the numerical priority (1 = highest-ranked project).

METHODS

Study area

Mainland Portugal has an area of 88,889 km^2, divided into 278 municipalities and five regions. The population is disproportionately distributed across the country, with the majority of people living near the coast, mainly in Lisbon, Coimbra, Braga, and Porto metropolitan areas. Mainland Portugal has five main regions: Norte, Centro, Lisboa e Vale do Tejo (hereafter simply the region of Lisboa), Alentejo, and Algarve. According to Köppen's classification system, the climate in Portugal is categorized as Mediterranean, with two subtypes: Mediterranean hot summer (Csa), primarily located in the southern region of the Tagus River, and Mediterranean warm summer (Csb), mainly found in the northern region of the Tagus River. The dominant land cover types in Portugal consist of forests (39%), croplands (26%), and shrublands (12%).[32] Coastal and northern areas are characterized by conifer forests, specifically *Pinus pinaster* Aiton and *Pinus pinea* L., as well as *Eucalyptus globulus* Labill. plantations. Inland mountainous areas display a mixture of grasslands and shrublands, interspersed with patches of deciduous forests consisting of *Quercus pyrenaica* Willd. and *Castanea sativa* Mill.

Portugal has been particularly affected by wildfires, with more than 4.6 million ha burned between 1984 and 2021, with particularly high incidence in the years 2003, 2005, and 2017.[64,65] On average, about 130 thousand ha burned each year in Portugal for the period 2000–2022, with roughly 2/3 of the total burned area resulting from fires larger than 500 ha, which represent less than 4% of the fires.

A recent study[29] identified four main fire regimes in Portugal, which can be summarized as (1) winter shrubland fires related to pastoralism, mostly characterizing the north region; (2) high incidence of small fire events located in areas with high population density, mostly located in the metropolitan areas of Lisbon, Porto, and Braga; (3) infrequent but large and intense wildfires, particularly in pine and eucalyptus forests, mostly situated in the center and Algarve but also present in the north; and (4) small fire events in agriculture and agroforestry areas, which occur throughout the country. Hence, fire occurrence is unevenly distributed, with the central and northern regions having overall higher fire frequency and susceptibility.[40]

A total of ca. 22% of the mainland terrestrial country area is protected under at least one decree.[66] The protected areas dataset includes national parks, nature reserves, protected landscapes, natural monuments, Natura 2000 sites, and private protected areas. Although protected areas have restricted uses and actions (particularly in sites classified as classes I and II by the IUCN[67]), the implementation of fuel reduction treatments is allowed upon previous approval by the Institute for Nature Conservation and Forests (ICNF). For this reason, protected areas were considered as available for management and were included in the modeled treatment scenarios.

Hazard metrics and scenario modeling overview

The Portuguese fire plan calls for about 250,000–300,000 ha per year of regularly managed fuels by 2030 using mechanical means, grazing, and prescribed burning. These treatments along with other prevention measures are to be implemented to broadly address three national goals: (1) reduce the cumulative burned area by around half, (2) reduce the percentage of fires larger than 500 ha by around half, and (3) substantially reduce the loss of lives in rural fires. We selected three wildfire hazard metrics that potentially could help achieve these goals when used to prioritize fuel management projects and treatments

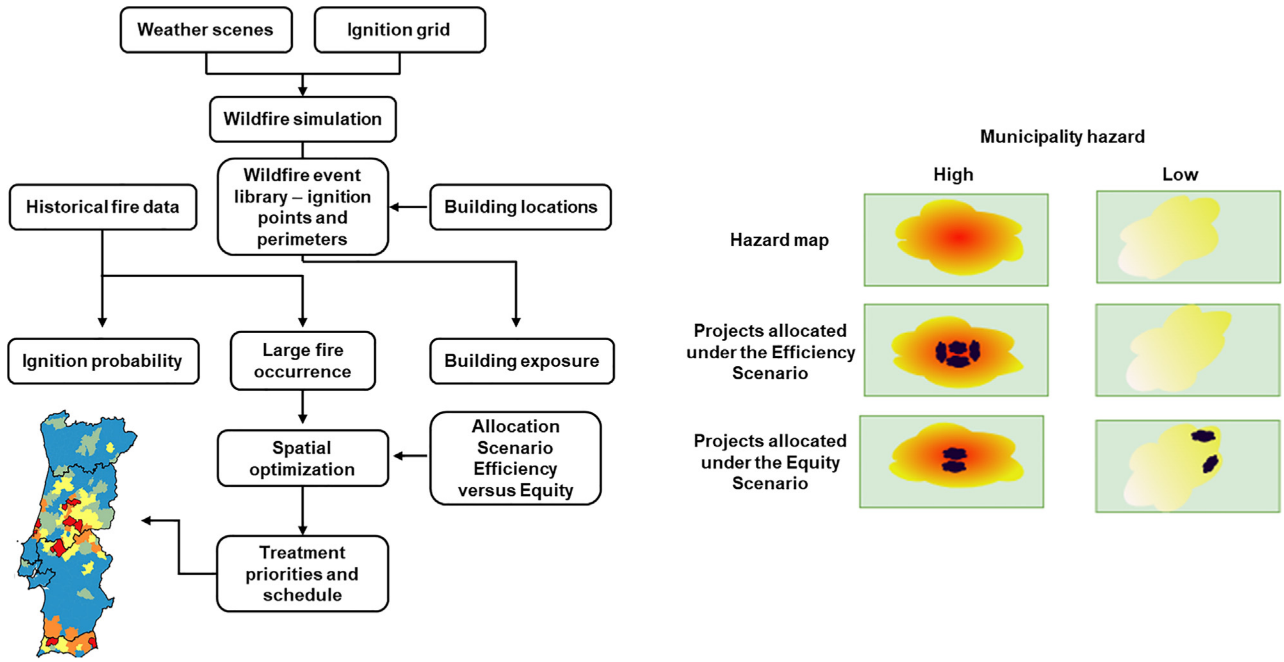

Figure 8. Overview of the analysis process to build hazard metrics and use them in the ForSys model to generate national fuel treatment scenarios in Portugal

Left: wildfire simulation outputs and historical wildfire data were used to create spatial data on ignition probability, large fire occurrence, and building exposure. These data were then used as fuel treatment priorities in the ForSys scenario model. Right: conceptual diagram of the alternative allocation scenarios (efficiency versus equity) modeled to address wildfire hazard in each of the 278 municipalities in Portugal. Polygons represent levels of hazard from high (red) to low (white) for two hypothetical municipalities and four fuel treatment projects. Projects were allocated to municipalities based on their level of hazard (efficiency scenario, middle row) or equally among all municipalities (equity scenario, bottom row). Note that projects are spatially optimized within each municipality to treat areas with the highest hazard.

within them, namely observed location of large wildfires, predicted exposure of buildings to wildfire, and historic ignition frequency (henceforth large wildfires, building exposure, and ignition probability, respectively). The estimation process for the hazard metrics used both empirical and simulated data on wildfires (Figure 8, left panel) as detailed below. These data were then used in a scenario modeling process to allocate treatment among the 278 municipalities in Portugal using two different scenarios (equity versus efficiency, Figure 8, right panel). In this process, the treatments were organized into 100 ha projects and spatially optimized within each municipality to target the hazard metrics. The development of the three hazard metrics is described below.

Ignition probability

We created the ignition probability surface from the historical ignition points (2001–2022) for Portugal[68] and bordering Spain.[69] We used all ignitions regardless of the cause and resulting burned area. The ignition points were used to create a smoothed raster coverage (with a cell size of 100 × 100 m^2) using the kernel density procedure in ArcMap[70] to generate an ignition probability (Figure 9). After testing a range of parameters, we found that a fixed bandwidth of 10 km generated a coverage that broadly captured the spatial variation in ignitions without overly smoothing the ignition data into areas without observations.[71] Non-burnable areas were then masked out of the grid based on the national fuel model layer.[72]

Large wildfires

The average size of wildfires was estimated using the historical ignition points for the period of 2001 to 2022.[68] We attributed the area burned by each fire perimeter to its ignition point and then filtered the data to only include fires that escaped initial suppression attack and grew to ≥50 ha (n = 5,736). The ignition points were then used to create a smoothed raster (cell size of 100 × 100 m^2) coverage using inverse distance weighting procedure in ArcMap.[70] As with the ignition data, we tested a range of parameters and found that a fixed search radius of 10 km and a minimum sample of 5 ignition points generated a coverage that adequately captured the local variation in large fires without overly smoothing the data (Figure 9). Non-burnable areas were then masked out of the grid based on the national fuel model layer.[72]

Building exposure to wildfire

Spatial point data on residential buildings were acquired from the Instituto Nacional de Estatística.[73] The dataset encompassed approximately 3.3 million residential building locations throughout mainland Portugal. For the analysis, buildings situated in non-burnable urban and industrial developed areas (i.e., artificial land covers)[32] were excluded from consideration.

We used a data library of simulated wildfires generated in a prior study[31] using the FConstMTT, an open-source mechanistic fire spread model.[74] FConstMTT is essentially a command line version of FlamMap[75,76] that simulates fire spread using gridded

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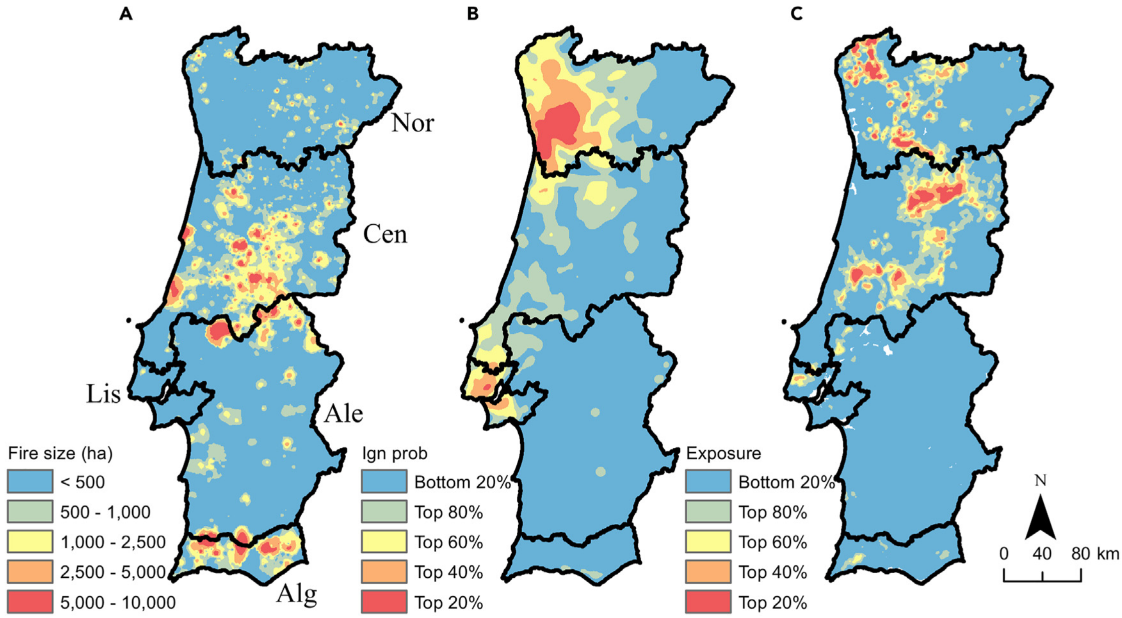

Figure 9. Spatial distribution of fire hazard metrics used as priorities for fuel management

(A and B) Fire size (A) and ignition probability (B) were estimated from historical fire databases over the periods 2001 to 2022.

(C) Building exposure (C) was estimated from wildfire simulation libraries as described in text. Regions: nor, Norte; Cen, Centro; lis, Lisboa e Vale do Tejo; ale, Alentejo; Alg, Algarve.

input data on surface and canopy fuels, weather, and other parameters. FlamMap (and FConstMTT to a lesser extent) has been widely used by both researchers and practitioners in the US and the EU.[77–80] The development of the simulation library has been described in detail,[31] including extensive calibration to replicate the observed fire size distribution and annual burned areas in mainland Portugal. The fire simulation library for Portugal contains a shapefile of fire perimeters (n = 1,654,448) and 100 × 100 m^2 grids of predicted flame length (meters) and annual burn probability.[31]

We used the simulated wildfires[31] (versus empirical) to map the predicted exposure of buildings since the former provided a much larger sample of observations on fires that potentially intersect developed areas. We first intersected each simulated fire perimeter with residential building locations and tabulated the number of buildings within the perimeter. This value was assigned to the ignition point of the respective fire perimeter to build a coverage that identified the source location of building exposure from wildfire. The ignition points attributed to the building count from the associated perimeter were then smoothed using inverse distance weighting in ArcMap with a search radius of 2,500 m and a power of 0.5 to generate a 90 m raster of building exposure. To annualize the exposure grid, we multiplied the total exposure by an ignition probability grid (ignitions/ha/year) created with the ArcMap point density tool (Figure 9). Parameters for the latter were a search radius of 2,500 m and the population field set to ignitions per year. The product was a smoothed building exposure raster (cell size of 100 × 100 m^2), where each cell represented the expected annual number of buildings exposed by wildfire igniting in the surrounding hectare.

Treatment scenarios

We used the Portuguese government land use/land cover data[32] to define homogenous treatment parcels for mainland Portugal. The larger parcels (>10 ha) were further divided using a 5 ha hexagon tessellation in ArcMap. Parcels containing artificial areas, water bodies, and annually cultivated cropland[32] were considered unavailable for treatments, resulting in a total of 1.6 million treatable parcels. Note that orchards and olive groves were considered as treatable areas to be consistent with landowner activities in the Mediterranean basin.[81] Although annual crops are a significant source of ignitions as part of crop residue disposal in the Mediterranean region, their contribution to total burnt area is less than 7%.[81] The average size of available treatment units was 4.2 ha, which falls within the observed size of prescribed burns conducted in Portugal.[82] Each parcel was populated with average fire size, ignition probability, and exposure of buildings. Parcel values for the first two variables resulted from the mean value of the raster cells in each parcel, while building exposure to wildfires resulted from the sum of all raster cells in each parcel. Other relevant data, such as administrative boundaries (e.g., municipality and region, land use, etc.), were also included in the parcels.

We then modeled two investment allocation strategies for the three hazard metrics (building exposure to wildfires, ignition probability, and incidence of large wildfires; Table 1; Figure 9). In the equity scenario, treatments were allocated equally among the 278 municipalities, with the treatments organized into 100 ha project areas that were spatially optimized to treat the highest level of each hazard within the municipality. In each scenario, the process of building optimized projects was terminated

Table 1. Description of the seven national treatment scenarios simulated for Portugal

Treatment allocation strategy		
Equity	Efficiency	Random variant of the efficiency scenario
Each municipality is allocated treatments equally	treatments prioritized at national scale based on hazard	treatments allocated by randomly implementing projects from the efficiency scenario

Three hazard metrics (large wildfires, exposure of buildings to wildfire, and ignition frequency) were used as priorities in the scenario optimization model under two different spatial allocation schemes, equity versus efficiency (Figure 8). Equity allocated treatments to each of the 278 municipalities proportional to their total amount of risk meaning that all municipalities received some level of investments in treatment. In the efficiency scenario, treatments were spatially allocated based on risk at the scale of the individual treatment parcel. In all scenarios, the total treatment was constrained to 80% of the total value of each risk metric, and treatment parcels were optimized into 100 ha project areas for implementation. The random variant of the efficiency scenario selected projects for implementation randomly from the projects identified in the efficiency scenario to demonstrate the benefit of prioritizing projects based on the hazard metrics. See text for additional details.

when the parcels responsible for 80% of each hazard metric were identified as treatments. This process created a sequence of prioritized project areas for each municipality that could be considered a realistic, on-the-ground scenario for implementing the national priorities. In the efficiency scenario, the optimized sequence of projects in the equity scenario was re-sorted without considering municipality boundaries and prioritized for implementation until the same total area was treated. In other words, projects were prioritized based on the total hazard they treated, without regard to the municipality. Thus, two allocation scenarios were modeled for three fire hazard treatment priorities, for a total of 6 scenarios. A random variant of the efficiency scenario was also simulated to measure the gain in efficiency when a systematic approach is used to prioritize projects. The random scenario was created by randomly selecting project areas from the efficiency scenario for implementation.

Clustering the treatments into 100 ha project areas was intended to replicate operational practices for fuel reduction activities, and the project size was chosen after consultation with AGIF planning staff, who guided many of the choices of other parameters in the study, as well. Although under current fuel treatment practices projects are typically much smaller than this size (1–10 ha) owing to fragmented land parcel ownership,[82] there is ample evidence that projects need to be substantially larger to significantly affect large fire behavior.[25] Due to patches of non-treatable areas (e.g., water bodies), the 100 target was not feasible for a small percentage of the projects. Projects that failed to meet a minimum threshold of 30 ha were excluded from the analysis.

We used the scenario planning model ForSys[28] to generate spatially optimized projects for each scenario. ForSys was specifically designed to build landscape management scenarios for forest restoration and risk and hazard reduction and has found applications in several case studies in the Mediterranean region[83–85] and elsewhere.[28] The ForSys algorithm employs a greedy search heuristic that tests each parcel as a seed to build a surrounding project area and identifies those that need treatments based on treatment thresholds.[86] The search continues, adding adjacent parcels, until the treatment area constraints are met. The process is repeated to test all parcels as a seed, and the project that maximizes one or more objectives is identified. The optimality of ForSys solutions was compared with mathematical programming formulations and found to be within 5%–10% of the absolute optimum for single-objective formulations.[87] Due to computational requirements, we did not model the effect of treatment on fire behavior, a task that would have required re-running the wildfire simulations for all the scenarios. We assumed that if a parcel is treated, fire exposure was substantially reduced,[49] an assumption that is necessary to simulate alternative scenarios at national scales. As more refined data becomes available on different treatment types and their effects, the modeling can be expanded to include post-treatment fire behavior.

For all scenarios, a hypothetical implementation plan was created where the optimized projects were implemented over 10 years by assuming treatment on 250,000 ha per year (ca. 2,500 projects per year). We analyzed each scenario in terms of its rate of progress over the 10-year plan in terms of treating high-hazard areas and the total area required to treat 80% of the national hazard for each hazard metric. We were particularly interested in the change in treatment leverage (hazard treated per ha) as projects were implemented and the existence of inflection points for diminishing returns over the 10-year plan. In prior work,[26] we observed substantial reduction in the treatment leverage when more than 80% of building exposure was treated and hence used this level for comparisons.

Analyzing trade-offs and co-optimality

We quantified trade-offs using Pareto frontiers with a weighted objective function where weights for each hazard metric were varied from 0 to 5 in all combinations with increments of one. After removing duplicate weight combinations (e.g., 1, 1, 1 being the same as 2, 2, 2), this process generated 175 distinct solutions for each municipality of alternative treatment scenarios. The resulting multi-objective values were then graphed as a Pareto frontier to visualize trade-offs associated with prioritizing one hazard versus another in each municipality and for the entire country.

To standardize values across hazard metrics, the raw values for each parcel were adjusted to represent the percentage of the maximum value within the corresponding datasets. This normalization helped eliminate potential impacts stemming from differences in measurement scales. Trade-offs for the equity scenario were assessed by sorting the projects to implement based on their importance for each municipality, whereas the efficiency scenario was created by sorting the projects to implement based on their national importance, ignoring municipality boundaries.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Alan Ager (alan.ager@oregonstate.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

Data and code used in this paper will be shared by the lead contact upon request.

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AUTHOR CONTRIBUTIONS

A.A.: conceptualization, methodology, software, validation, resources, writing – original draft, writing – review & editing, and supervision. B.A.A.: conceptualization, methodology, formal analysis, investigation, visualization, writing – original draft, and writing – review & editing. J.M.C.P.: validation, supervision, and writing – review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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