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Understanding the Impact of Different Landscape-Level Fuel Management Strategies on Wildfire Hazard in Central Portugal

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Abstract: The extreme 2017 fire season in Portugal led to widespread recognition of the need for a paradigm shift in forest and wildfire management. We focused our study on Alvares, a parish in central Portugal located in a fire-prone area, which had 60% of its area burned in 2017. We evaluated how different fuel treatment strategies may reduce wildfire hazard in Alvares through (i) a fuel break network with different extents corresponding to different levels of priority and (ii) random fuel treatments resulting from a potential increase in stand-level management intensity. To assess this, we developed a stochastic wildfire simulation system (FUNC-SIM) that integrates uncertainties in fuel distribution over the landscape. If the landscape remains unchanged, Alvares will have large burn probabilities in the north, northeast and center-east areas of the parish that are very often associated with high fireline intensities. The different fuel treatment scenarios decreased burned area between 12.1–31.2%, resulting from 1–4.6% increases in the annual treatment area and reduced the likelihood of wildfires larger than 5000 ha by 10–40%. On average, simulated burned area decreased 0.22% per each ha treated, and cost-effectiveness decreased with increasing area treated. Overall, both fuel treatment strategies effectively reduced wildfire hazard and should be part of a larger, holistic and integrated plan to reduce the vulnerability of the Alvares parish to wildfires.

Keywords: fire spread; modeling; stochastic; fuel breaks; forest management; uncertainty

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1. Introduction

The 2017 fire season in Portugal was unprecedented, with a record of 540,000 ha burned, a total of 119 fatalities and millions of euros in losses and damages, resulting from several extreme wildfires [1–3]. The weight of these numbers shocked society in general, leading to widespread recognition of the need for a paradigm shift in forest and fire management. Other countries also suffered extreme wildfires in recent years, such as Chile [4], Brazil and Bolivia [5], Australia [6] and the USA [7].

The Portuguese 2017 fire season was amplified by a severe drought and the occurrence of atmospheric conditions conducive to large wildfires [8–12]. Adding to these factors, Portugal has extensive areas of undermanaged forests and shrublands that facilitate the occurrence of frequent, very large and uncontrolled wildfires [13]. Overall, climate change will likely create conditions for more frequent wildfires and extreme fire behavior in the future [14], potentially leading to severe fire seasons, such as that experienced in 2017.

Effective strategies are necessary to reduce the likelihood of severe fire seasons in the future. The landscape needs to be shaped to promote fire-resiliency in the medium and long term. One of the possibilities is to reduce landscape flammability and fuel continuity

by managing fuels at the landscape level and, therefore, potentially offsetting the effects of current and future weather conditions on wildfire spread and behavior [15]. To be an effective wildfire hazard reduction tool, landscape fuel management alternatives should be considered as part of a holistic and integrated approach, interconnecting the actors and phases of complex wildfires [16–18].

Science can contribute with knowledge and tools for more effective landscape fuel management, thus improving planning and decision-making. Previous research has shown how fire spread simulation tools can be used to assess wildfire exposure at the landscape level [19–21], quantify associated risk [22–24], study wildfire transmission [25,26] and identify optimal fuel treatment location [27,28]. These simulation tools have also proven useful to quantify the potential impact of climate change on wildfire incidence [29] and of mitigation measures on post-fire erosion and water contamination [30,31].

In the aftermath of the 2017 wildfires in Portugal, a group of landowners from the civil parish of Alvares, municipality of Góis, in central Portugal, requested support from the Forest Research Centre (University of Lisbon) to develop a plan for the rehabilitation of an extensively burned area in a way that would reduce its vulnerability to large wildfires. In central Portugal, large wildfires are very often associated with high intensities, severe damages and pose important threats to human health and both economic and forest sustainability [10,11]. Besides the 2017 wildfire, which burned 60% of its area, wildfires in Alvares over the last 40 years burned the equivalent to the total area of the parish twice. Such a short fire cycle is driven by long-term demographic and land-use changes common to other parts of rural Portugal, namely population decrease and aging [32], abandonment of agricultural lands and expansion of forest and shrubland area [16] and increasing frequency of droughts and heatwaves as a result of climate change [33]. In addition, highly fragmented land ownership, with numerous small land properties owned by a very large number of landowners [34] with low-income levels, leads to undermanagement of forests and pasture areas. These environmental and socioeconomic factors have contributed to developing a fire regime dominated by large wildfires.

The overarching project had the main goal of developing proposals to reduce the vulnerability of the Alvares parish to large wildfires based on three more specific objectives: (1) to reduce the frequency of large fires; (2) to improve the safety of people and assets; and (3) to strengthen the local economy. This integrated approach contributes to supporting the necessary change in the forest management paradigm and developing fire-resilient landscapes [35]. Here, we evaluated how different fuel treatment strategies can reduce wildfire hazard in Alvares. Parallel studies have addressed the other two pillars [34,36,37]. Two main strategies were analyzed: fuel breaks (linear treatment units) and dispersed random fuel treatments in the landscape (areal treatment units). Both strategies had different levels of implementation (i.e., extent in the landscape) and, when combined, resulted in twelve different fuel management scenarios for the parish. These strategies were chosen because they have been commonly applied in Portugal [25,38], and references therein] and because they allow achieving the other two specific objectives for the Alvares parish [35]. In this work, the objective was to understand how these fuel management scenarios can change future wildfire hazard, then maintaining the landscape similar to conditions prevailing at the time of the 2017 wildfire. It is beyond the scope of the current work to optimize fuel treatments location and quantify the potential impacts of climate change on wildfire hazard.

2. Study Area

The Alvares parish has an extent of 10,057 ha and is located in the center of Portugal (Figure 1). It has rugged terrain, ranging in elevation from 300 m in the south to about 1200 m in the north, coinciding with the Lousã mountain. Along this elevation gradient, precipitation ranges from 1100 mm to 1700 mm per year [39]. The summer months (July and August) are usually dry and receive, on average, around 15–20 mm of precipitation each.

The Alvares landscape has suffered profound changes in the last century, shifting from a landscape dominated by shrubland, pastures and agricultural areas, with less than 10% forest area [35], to a forest-dominated landscape (ca. 90%), composed mainly of *Eucalyptus* sp. (mainly Tasmanian blue gum and shinning gum, hereafter eucalypt, covering 53%) and *Pinus pinaster* Aiton (maritime pine ca. 30%, hereafter pine) (Figure 1; Portuguese Land Cover Map 2015: COS2015, Direção Geral do Território). Both are harvestable commodities: eucalypt is used mainly for the pulp and paper industry, and pine is mainly used for timber. Like many other regions of the country, the Alvares parish underwent a pronounced population loss, with a 75% decrease in the number of inhabitants from 1960 to 2011 [40,41]. More than 96% of the lands are privately owned, by more than 3000 landowners, including two paper industry companies [35].

The Alvares parish had 42 wildfires in the 1975–2017 period, which burned more than 20,000 ha, the equivalent to twice of the parish extent. About 90% of the burned area resulted from 10 very large wildfires that burned over 1000 ha each. Many areas of the parish burned more than 3 times over the past 43 years (see Figure 2a). The last very large wildfire occurred in June 2017 and was the most destructive on record, burning around 60% of the parish area. These large wildfires are usually associated with high severity [10,11], are an important threat to the safety of people and assets [37] and hamper economic sustainability [36].

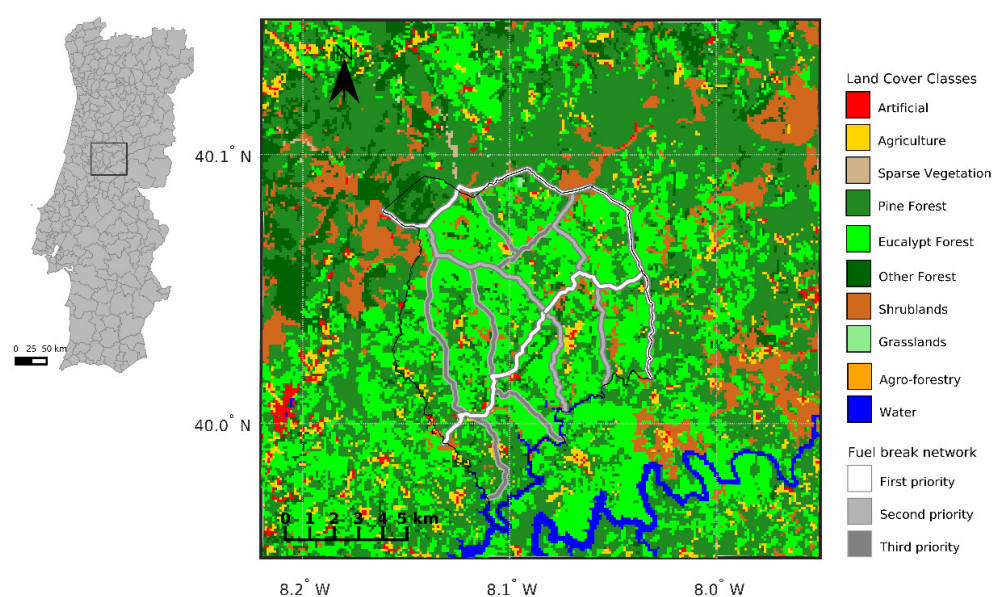


Figure 1. Study region: land cover and spatial context. Land cover classes derived from the Portuguese 2015 land use map; fuel break network design is explained in Section 3.2.

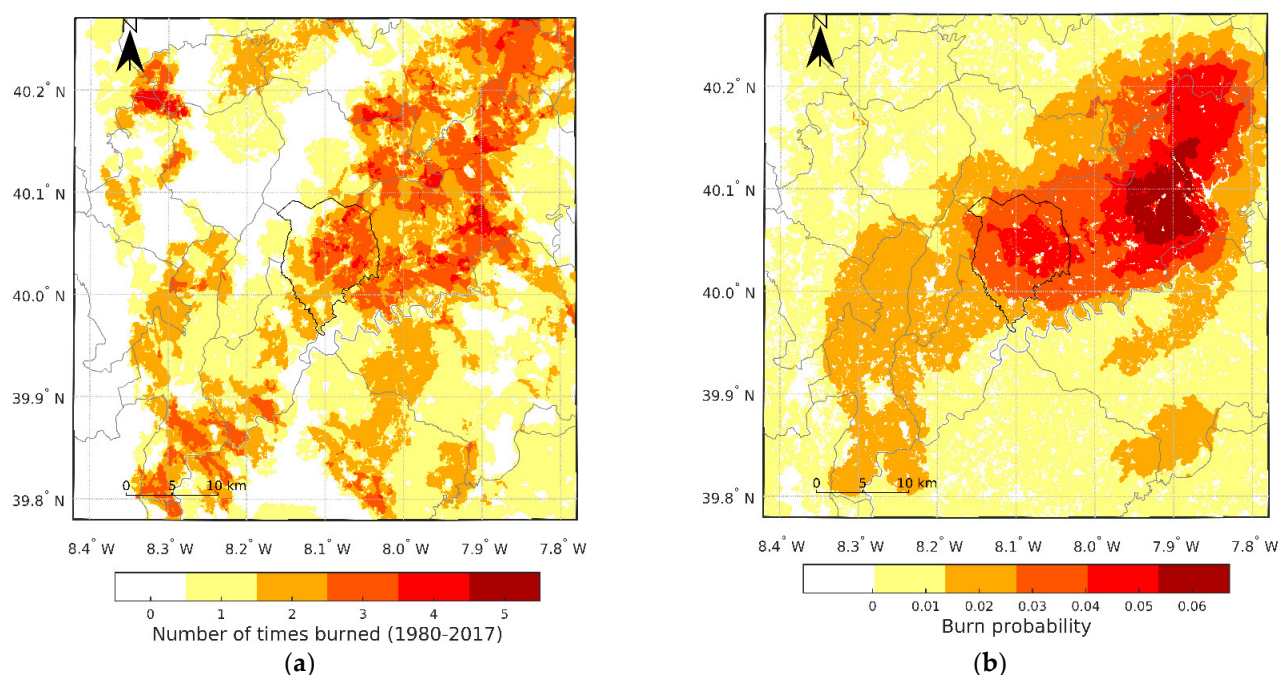


Figure 2. Spatial distribution of (a) observed frequency of very large wildfires (>1000 ha) between 1980 and 2017 and (b) predicted burn probability. Gray lines represent municipalities; black lines represent the Alvares parish boundary.

3. Materials and Methods

3.1. Fire Spread Simulation

3.1.1. Data and Modeling Approach

To assess how changes in the landscape affect wildfire hazard, we developed a stochastic fire simulation system that explicitly integrates uncertainty (fire uncertainty simulation system; FUNC-SIM). It requires input data on weather, fuel and ignition to simulate the growth of thousands of hypothetical individual wildfires, each simulated with the FARSITE software [42]. The modeling approach was focused on large wildfires that burned over 1000 ha each since they corresponded to 90% of the area burned over the last 40 years. The study region was defined as a 55 km × 55 km window centered on the Alvares parish to consider wildfire transmission across the neighboring parishes and municipalities. The grid resolution was set to 100 m.

The dates of the large historical wildfires in the study region between 1980 and 2017 were extracted from the Portuguese Forest Service fire database [43]. Data before 1980 was not available. Temperature, relative humidity and wind data were derived from WRF 4 km-resolution forecasts [44] using the ERA-interim reanalysis from the European Centre for Medium-Range Weather Forecast as boundary conditions. Weather data were derived for a randomly defined sample of the fire dates ($N = 215$). WindNinja [45] was used to produce high-resolution (100 m) wind fields for each sampled fire date with a 3 h frequency. Most of the wind data had a prevailing frequency from NW/N direction, also associated with higher wind speed, followed by NE/E direction (Figure A1—Appendix A). Minimum daily relative humidity ranged between 10 and 70%, with a frequency peak around 30% (not shown), whereas maximum daily temperature ranged between 18 °C and 36 °C, with most data falling between 25 °C and 34 °C (not shown).

An ignition probability surface map was built based on the historical large wildfire records. This database has had profound changes over the last four decades. For the 1980–2000 period, the uncertainties were larger, and information was scarcer. Therefore, each ignition location was allocated to the centroid of the parish, where the largest burned area was recorded. From 2001 onwards, the uncertainties were smaller (although still large, see [46]), and the coordinates of each ignition point were used accordingly. The probability

surface was calculated using a kernel density function with a 10 km radius using the ignition points as inputs.

Fuel maps were created by establishing a correspondence key between the Portuguese land use and cover map and the fuel model typology of Fernandes (2005) [47] and Anderson (1982) [48], specifically for harvest residues. The fuel maps have large uncertainties due to several reasons, namely errors in the base land cover map, the correspondence procedure, and due to temporal fuel dynamics (e.g., [38,49]). For these reasons, the fuels in the landscape were represented using a stochastic approach. Throughout the entire work, the probability of occurrence of a fuel model was used to quantify the uncertainty associated with the fuel characterization of a given area. These uncertainties integrate the temporal fuel dynamics as well as different fuel management approaches. The probability of occurrence of each fuel model was defined for the dominant land cover types, i.e., eucalypt and pine forests and shrublands, considering their expected variability in space and time within a 40-year time horizon. These probabilities were defined based on expert knowledge and information collected from industrial forest managers, non-industrial landowners and the local forest owners' association. More details are described in Section 3.1.2, regarding the calibration of the fire simulation system and Section 3.3, regarding the simulation of the fuel management scenarios.

Eucalypt and pine stands were separated in industrial and non-industrial forests. Forest management approaches (FMA) in eucalypt plantations vary widely and are described in detail in Barreiro et al. [36]. Around 23% of the eucalypt area was industrial, and the remaining 77% was from non-industrial landowners divided in a set of four different FMA ordered by decreasing level of forest stand management intensity: “active” (15%), “semi-active” (15%), “quasi-absent” (35%) and “absent” (12%). The FMAs have different fuel management frequencies (Tables A1 and A2—Appendix A) that were translated into probabilities (Figure 3). For example, “active” owners harrow their eucalypt stands 5 times in three rotations (36 years), while “semi-active” owners harrow only 3 times and “quasi-absent” do not harrow their stands. The resulting fuel probabilities for each FMA were weighted by their proportion in the landscape (see [36]) to estimate the fuel model probability.

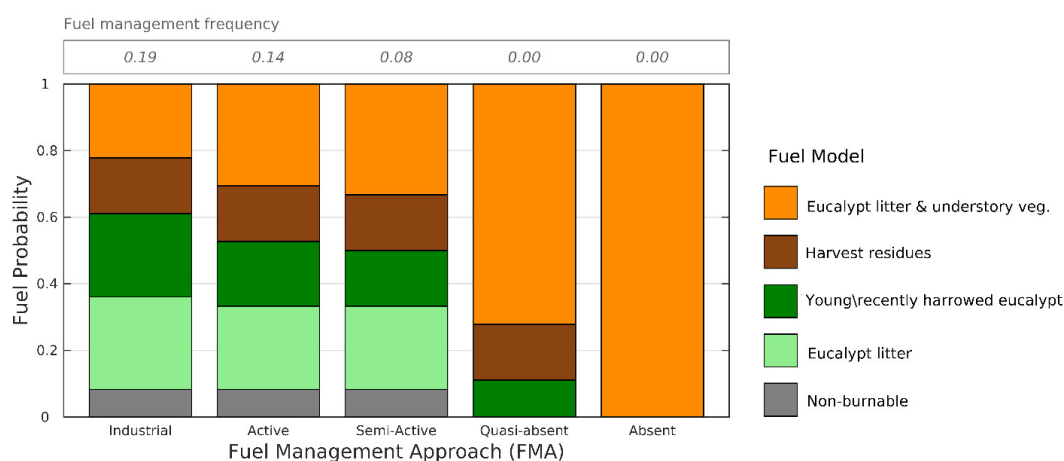


Figure 3. Fuel model probability for each forest management approach. Fuel management frequency was calculated as the fraction of harrowing operations in 40 years.

Much less information was available for pine stands, and therefore, the fuel model distribution was only based on two FMA, industrial and non-industrial, defined based on information collected from relevant stakeholders. The fuel model distribution in shrublands was defined based on the knowledge obtained in previous studies [10] since FMA does not apply. Table 1 summarizes fuel model probabilities for the major land cover types and uses in the study region.

The industrial FMA for eucalypt and pine stands was assigned based on the location of industrial properties. The spatial distribution of the non-industrial FMA was unknown. Therefore, it was assumed that the probability of occurrence of each FMA was equal to its relative proportion in the landscape. This assumption was only applied to eucalypt since only one FMA was considered for pine stands. The distributions were used to create stochastic fuel model maps for the study area (see Section 3.3).

The fire spread simulation system was run thousands of times, depending on the objective (for calibration, see Section 3.1.2; for scenario evaluation, see Section 3.3). In each iteration, a hypothetical wildfire was simulated, ignited at a given location randomly sampled based upon the ignition probability surface and spreading under specific weather conditions randomly sampled from the meteorological database generated for past large wildfires. For each simulation, a hypothetical fuel map was randomly generated (described in Section 3.3). Based on the information from the Portuguese Forest Service fire database, the duration of each simulated wildfire was set to 1, 2, 3 and 4 days with frequencies of 60%, 25%, 10% and 5%, respectively. Spotting and fire suppression were not simulated. Topographic variables were extracted from the shuttle radar topography mission (SRTM) data set [50]. Due to lack of information, canopy fuel variables were set constant based on expert knowledge. The thousands of simulated wildfires were combined to create a burn probability map, defined as the fraction of times a given grid cell burned. Each fire size was estimated and saved for further analysis. Each pixel burned with different estimated fireline intensities (FLI) depending on the prevailing fuel and weather conditions. As an indicative measure of fire resistance to control, for each pixel, the percentile 90 of all FLI values (i.e., corresponding to different simulated wildfires burning the same pixel) was calculated and reclassified according to the intensity classes described in Alexander and Lanoville (1989) [51]. The two higher fireline intensity classes were merged into a unique “very high and extreme” class.

Table 1. Fuel model probability distribution for each main land use/cover type and forest management approach (FMA).

Land Use/Cover and FMA	Fuel Model	Acronym	Probability
Non-industrial eucalypt forest	Non-burnable	NA	0.03
	Young or recently harrowed eucalypt stands	M-EUCd	0.12
	Eucalypt litter	F-EUC	0.10
	Eucalypt litter with understory vegetation	M-EUC	0.60
	Harvest residues ¹	NFFL11	0.14
Industrial eucalypt forest	Non-burnable	NA	0.13
	Young or recently harrowed eucalypt stands	M-EUCd	0.25
	Eucalypt litter	F-EUC	0.29
	Eucalypt litter with understory vegetation	M-EUC	0.21
	Harvest residues ¹	NFFL11	0.13
Non-industrial pine forest	Pine litter with understory vegetation	M-PIN	0.67
	Tall shrubs	V-Maa	0.33
Industrial pine forest	Pine litter	F-PIN	1.00
Shrublands and open forest	Tall shrubs	V-Maa	0.67
	Short shrubs	V-Mab	0.33

¹ fire behavior model 11 from Anderson, 1982 [48].

3.1.2. Model Calibration

The fire simulation system was calibrated for the 1980–2017 period using the historical weather conditions, the ignition probability surface and a stochastic fuel map. In this historical period, the availability of relevant information, such as the location and occupation of industrial properties, forest management approaches, etc., was much lower than for present and recent conditions. We created two fuel maps resulting from the correspondence with the Portuguese land use and cover maps for 1990 and 2015. The fuel model distributions were defined, assuming that each fuel map contributed equally to the estimated fuel model probability for each pixel. The simulation system was run 100,000 times.

The capability of the fire simulation system to reproduce historical fire patterns in the study region was assessed by comparing a set of the descriptors: (i) observed vs. estimated fire size frequency distribution and (ii) estimated burn probability surface vs. observed fire incidence in the historical period. For consistency, only wildfires larger than 1000 ha were considered. Model calibration was done by varying the Rate-of-Spread (ROS) adjustment factor available in FARSITE, using the same value for all fuel models.

3.2. Fuel Management Scenarios

We analyzed two types of fuel management strategies designed to reduce wildfire hazard at the landscape level: (i) the implementation of a fuel break network (linear strategy) and (ii) the dispersed random increase in the treated forest area at the stand-level (patch). A “business-as-usual” (BAU) reference option was also set, considering that the landscape would remain unchanged and correspond to the land cover present in 2015. These scenarios, including the BAU, may be considered as a set of potential options that authorities and landowners have for building a future landscape (e.g., [37]).

As part of a broader and larger spatial planning proposal for the Alvares parish (Pereira et al. 2019), a hypothetical fuel break network (FBN) with several segments was proposed by the National Institute for Nature Conservation and Forests (ICNF, the Portuguese Forest Service) (Figure 1). The fuel breaks are 120 m wide (minimum) and are meant to create vegetation discontinuities that will allow safer and more efficient fire suppression [25]. The network design was based on expert knowledge taking into account topography, the spatial distribution of the watersheds and fire history. The FBN had a total of 1220 ha divided by three different levels of priority: the first priority, corresponding to 1/3 of the total FBN extent; the second priority that combined with the first corresponds to 2/3 of the total extent (included the first priority); and the third priority that when combined with the latter priorities comprises the entire FBN (3/3). We assumed that fuel breaks would be managed, on average, every five years to keep fuel loads at levels unsuitable for surface fire spread.

Decreasing fuel hazard in the forest stands implies that fuel loads are regularly reduced with the indirect benefits of reducing potential fire size and intensity [52]. Based on meetings [36] and inquiries [34] with the forest association and landowners, we estimated that fuels were treated in around 40% of the non-industrial eucalypt area in Alvares, with a frequency that depends on the FMA. This corresponds to about 50% of the total eucalypt area, considering that fuel treatments in pulp industry areas are frequent and encompass a wide range of different treatment frequencies. It is estimated that around 420 ha are currently treated annually at the parish level, of which more than half (ca. 242 ha) are done by industrial owners. In relative terms, industry treated 19% of their eucalypt forest stands, although only 8% are treated at the parish level.

We evaluated how relative increases of about 20% (hereafter, moderate) and 30% (hereafter, high) in managed eucalypt areas could affect wildfire hazard in the parish. These increases were equivalent to an additional c.a. 750 ha and 1400 ha, respectively. Only eucalypt stands were considered due to their coverage and interest for the landowners and the amount of available information [34]. The increases in the managed area were

attained by replacing lower with higher intensity FMA, in different proportions depending on whether the increase was moderate or high [36]. Hence, it was assumed that the fraction of active landowners increase at the expense of decreasing those less active. The fraction of industrial and absent FMAs in the landscape were considered not to change over time. The remaining considerations of how the increases in the managed area were integrated are described in Section 3.3.

The effort in implementing the FBN was divided into four levels: none (equivalent to BAU), top priority, medium and top priority and the entire network. The increased managed forest stand area was separated into three levels: the same level of treatment (assumed to have the same as 2015), moderate and high. All levels were combined, resulting in twelve possible fuel management scenarios, with different increases in fuel treated area (Table 2).

Table 2. List of fuel management scenarios, respective acronyms and increase in total fuel treated area (absolute and per year, in brackets). “FBN” stands for fuel break network.

	Same Management	Moderate Management	High Management
FBN 0\3	0 ha ¹	754 ha or 52 ha y ⁻¹	1370 ha or 95 ha y ⁻¹
FBN 1\3	203 ha or 57 ha y ⁻¹	957 ha or 104 ha y ⁻¹	1573 ha or 147 ha y ⁻¹
FBN 3\3	368 ha or 104 ha y ⁻¹	1120 ha or 146 ha y ⁻¹	1738 ha or 189 ha y ⁻¹
FBN 3\3	576 ha or 163 ha y ⁻¹	1330 ha or 199 ha y ⁻¹	1946 ha or 242 ha y ⁻¹

¹ it is estimated that 420 ha are treated annually in this scenario (see text).

3.3. Simulating the Different Fuel Management Scenarios

The calibrated fire simulation system was used to understand the impact of the proposed fuel management scenarios on the potential future distribution of wildfires across the landscape. For this specific purpose, the ignition probability surface was defined using only the most recent and higher quality ignition data from the 2001–2017 period. Weather conditions for the entire historical period were used, thus changing climate conditions were not considered.

The Portuguese land cover and land use map of 2015 was used to create the reference fuel map. In properties managed by the pulp paper industry, the companies provided finer-scale land cover data that was used to create the fuel map. Each property was considered to have homogeneous fuels. For non-industrial forest stands and shrublands, the landscape was divided into 5000 randomly defined patches using Thiessen polygons for computational reasons. The patch size distribution ranged between 1 ha to 119 ha, with an average size of 38 ha (Figure A2—Appendix B). This value was significantly larger than the average property size (average of 0.5 ha). However, a lower value was not possible to implement due to computation constraints. A fuel model was assigned to each patch based on the fuel model probabilities previously defined (see Table 1). These steps were used to create a stochastic fuel map for each simulation of the BAU fuel management option.

The potential fuel management scenarios were analyzed to change the distribution of fuels in the landscape (Table 3). Increasing treated forest stand area and/or implementing fuel breaks implies that a potential future wildfire will have a higher probability of encountering less hazardous fuels.

Regarding the fuel break strategy, it was assumed that in the year of implementation or maintenance, the area of intervention was unburnable and that in the following years, grass and shrub fuels built up until fuel reduction operation could be performed five years later (Table 3). The increase in treated forest stand area affected the fuel distribution in eucalypts stands in a scattered and random way, mirroring current practice. For the moderate and high increase scenarios, the fraction of the landscape covered with “active” and “semi-active” FMA increased at the expense of a decrease in the “quasi-absent” FMA [36].

As previously mentioned, the fuel treatment frequency varies with the FMA, contrary to the fuel break approach.

Table 3. Distribution of fuel models in the landscape for each fuel management scenario.

Land Use/Cover and Scenario	Fuel Model	Acronym	Probability
Non-industrial eucalypt forest: business as usual	Non-burnable	NA	0.03
	Young or recently harrowed eucalypt stands	M-EUCd	0.12
	Eucalypt litter	F-EUC	0.10
	Eucalypt litter with understory vegetation	M-EUC	0.60
	Harvest residues ¹	NFFL11	0.14
Non-industrial eucalypt forest: moderate increase in managed forest stands	Non-burnable	NA	0.05
	Young or recently harrowed eucalypt stands	M-EUCd	0.13
	Eucalypt litter	F-EUC	0.15
	Eucalypt litter with understory vegetation	M-EUC	0.53
	Harvest residues ¹	NFFL11	0.14
Non-industrial eucalypt forest: high increase in managed forest stands	Non-burnable	NA	0.06
	Young or recently harrowed eucalypt stands	M-EUCd	0.15
	Eucalypt litter	F-EUC	0.19
	Eucalypt litter with understory vegetation	M-EUC	0.47
	Harvest residues ¹	NFFL11	0.14
Fuel breaks	Non-burnable	NA	0.20
	Discontinuous shrubs and herbs	V-MH	0.60
	Short shrubs	V-Mab	0.20

¹ fire behavior model 11 from Anderson, 1982 [48].

The simulation for the BAU option was run 100,000 times. The fireshed (e.g., [26]) was estimated as the convex area for which a potential ignition could lead to a wildfire that would partially burn the Alvares parish. To reduce computational time, only the ignitions overlapping the fireshed area (ca. 28,000) were selected and used to run the fire spread simulations of the remaining fuel management scenarios.

The combination of different fuel management options was expected to change the Alvares parish's exposure to wildfire. These impacts were assessed by quantifying changes in fire size distribution, total simulated burned area and burn probability over the landscape. Additionally, we analyzed the relationship between the increase in the annual treated area and the reduction of the total estimated burned area as a rough indicator of effectiveness. Comparisons were made by analyzing relative changes in these indicators compared to the BAU option.

4. Results

4.1. Model Calibration

The best model calibration was achieved using a rate-of-spread adjustment factor of 1. Overall, the predicted fire size distribution was similar to the observed large wildfires size distribution between 1980 and 2017 (N = 76, Figure 4). The fire size histograms peaked at 1500 ha (observed) and 1000 ha (estimated). The largest differences were observed for

the 1000 ha and 2000 ha classes, where fire size was slightly underestimated and for wild-fires smaller than 1000 ha, where there was a clear overestimation.

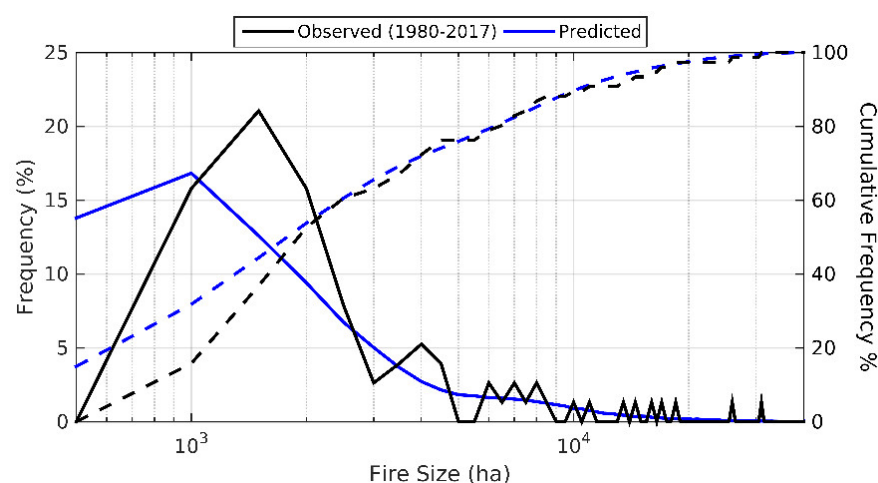


Figure 4. Comparison between observed and predicted fire size on a logarithmic scale. Filled lines represent frequency; dashed lines represent cumulative frequency (both in %).

The spatial patterns of observed wildfire frequency since 1980 (Figure 2a) were very similar to the estimated burn probability in Alvares and surrounding areas (Figure 2b). The largest burn probabilities coincided with the eastern and northeastern parts of the study region, including part of Alvares. The largest differences between estimated burned probability and observed fire frequency were observed in the northwest of the Alvares parish, suggesting an overestimation of burn probability and in the northwestern and southern areas of the study region, exhibiting some local underestimation of hotspots that burned 3 and 4 times since 1980. The northwest part has had extensive forest areas managed by the pulp paper industry and the Portuguese Forest Service, a dense network of detection and suppression infrastructures (e.g., lookouts, runaway) and very good accessibilities that can partially explain the low fire history.

Overall, estimated burn probability increases with observed wildfire frequency and vice versa (Figure 5). Variability in burn probability also increases in wildfire frequency, particularly for areas that burned 3 and 4 times since 1980. Overall, the results show that the calibrated modeling system accurately reproduces the historical wildfire patterns, both in terms of fire size and spatial distribution, particularly within and in the close vicinity of the Alvares parish.

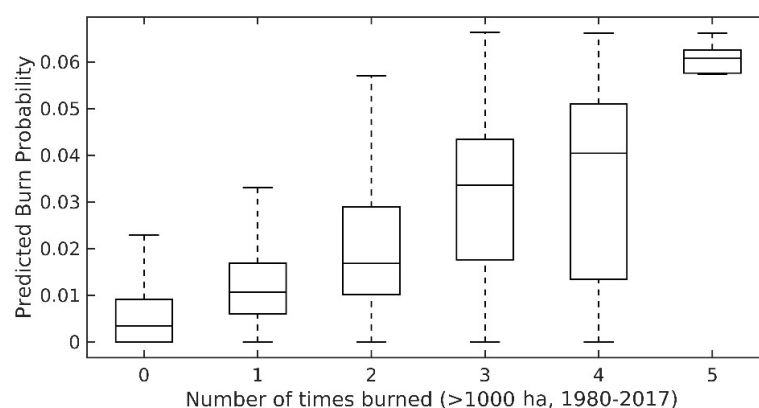


Figure 5. Comparison between the spatial distribution of observed frequency of very large wild-fires between 1980 and 2017 and predicted burn probability.

4.2. Wildfire Hazard in the Business-as-Usual (BAU) Scenario

The calibrated fire modeling system was used to estimate wildfire hazard in the Alvares parish for the BAU option. Assuming that the landscape remains unchanged, higher burn probabilities were estimated to occur in the north, northeast and center-east areas of the parish (Figure 6), showing very similar patterns to the historical calibration (see Figure 2). Most of the parish had moderate (21%) or high (63%) estimated fireline intensity. Very high and extreme fireline intensity occupied 8.6% of the parish area. Higher intensity coincided with large, contiguous shrubland areas, while lower intensities occurred in managed forest areas and short-needle coniferous forests (in the NW corner). Areas with higher burn probability were mostly associated with high fireline intensity (75%) and to a lower extent with very high and extreme fireline intensity (14%). Areas with lower burn probabilities were mostly associated with moderate (28%) or high (46%) intensity. Results suggest that wildfires will very often require large air tankers for effective suppression (high and very high classes) and sometimes will be beyond suppression capability (i.e., the extreme class).

Results showed very large areas in the vicinity of the parish border with high, very high or extreme simulated fireline intensity. The northern and eastern borders stand out because of coincidence with higher estimated burn probability. Given these results and the dominant winds associated with large wildfires, the potential effectiveness of fuel breaks in creating suppression opportunities for transmitted wildfires must be evaluated carefully.

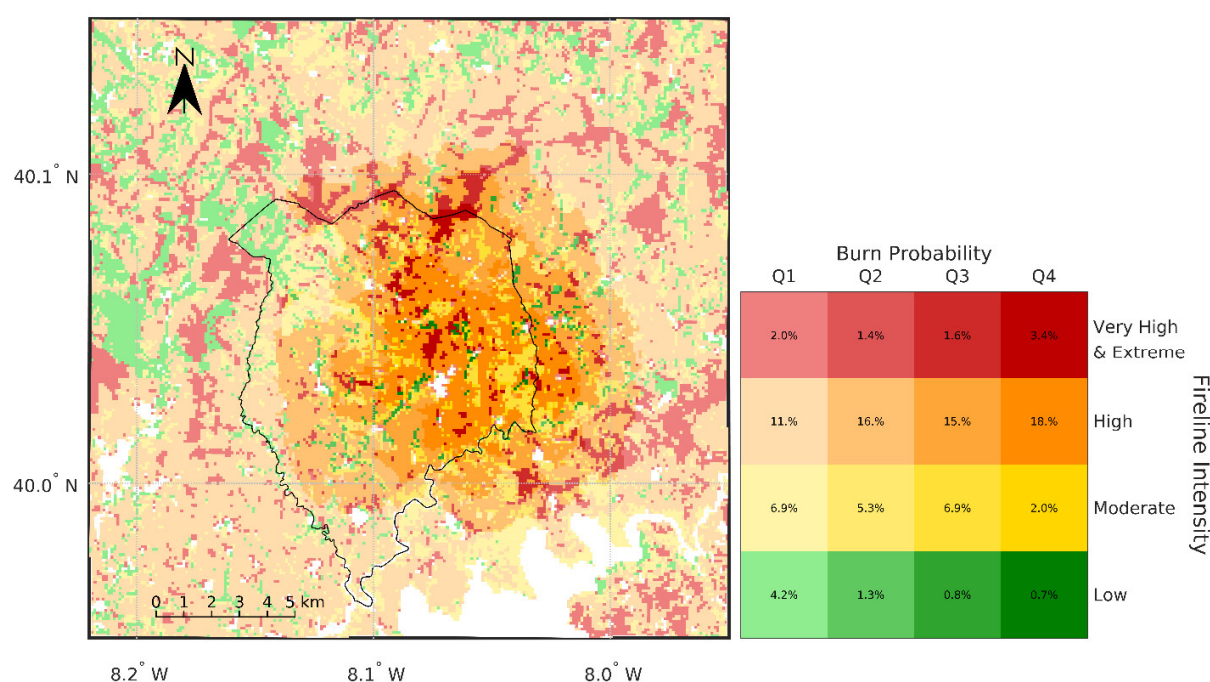


Figure 6. Combination of simulated burn probability and fireline intensity in the Alvares parish and close surroundings. Q1, Q2, Q3 and Q4 are the quartiles of burn probability.

The estimated BAU fireshed stretched away from the parish limits in the northwestern, northern, northeastern and eastern directions, reaching distances up to 18 km in the latter directions (Figure 7). The shape of the fireshed was consistent with the frequency of wind direction and wind intensity associated with the largest historical wildfires (Figure A1—Appendix A). Historical and BAU estimated firesheds were similar and contained all the burned area footprint during the 1980–2017 period (see Figure A3—Appendix B).

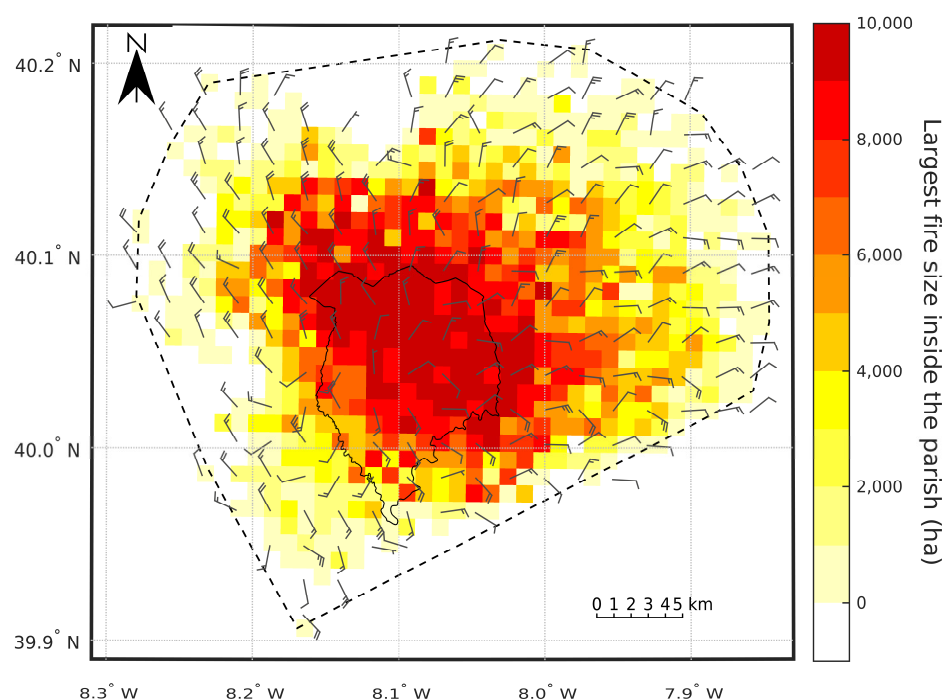


Figure 7. Largest burned area extent (ha) inside the Alvares parish from wildfires originating at each pixel location and respective dominant wind direction (BAU option). The dashed line represents the fireshed.

The fireshed extent and shape suggest that, for example, a wildfire starting 18 km eastwards of the parish, under suitable weather conditions, can burn part of the parish in the following hours. Figure 7 also shows that wildfires starting inside the parish, with the exception of the south/southwestern part, have the potential to generate wildfires that can burn over 80% of the Alvares parish. Wildfires starting in the northwestern to eastern directions up to a distance of 5–6 km and associated with dominant wind directions depicted in Figure 7 have the largest potential to burn very large extents of the parish.

4.3. Impact of Uncertainty on the Estimation of Wildfire Hazard

Integrating the uncertainty in fuel model distribution over the landscape had an important impact on the stochastic simulation of wildfires. On average, the estimated fire size was reduced by 25 to 30% when uncertainty was integrated (Figure A4—Appendix B), decreasing the burn probability over the landscape (Figure 8). This was particularly noticeable in treated forest areas due to the assumptions made regarding the fuel model distributions and due to the very large forest cover in the Alvares parish.

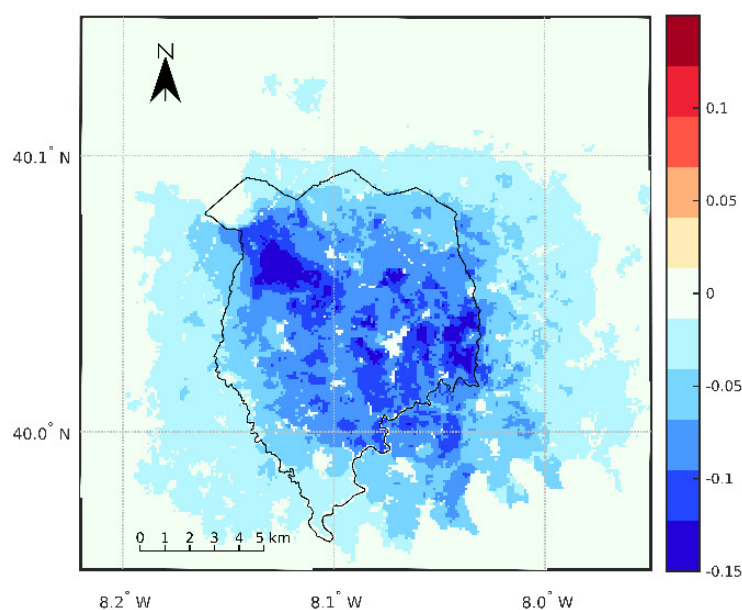


Figure 8. Impact of integrating fuel uncertainty in the spatial distribution of estimated burn probability. The color bar shows the difference in burn probability calculated as: “with uncertainty”–“without uncertainty”.

The impact of integrating fuel uncertainty was largest in treated eucalypt and pine forests, decreasing both the estimated burn probability and fireline intensity (Figure 9). This suggests that incorporating fuel treatment in stochastic fire spread simulations can be attained by considering uncertainties in fuel model distribution.

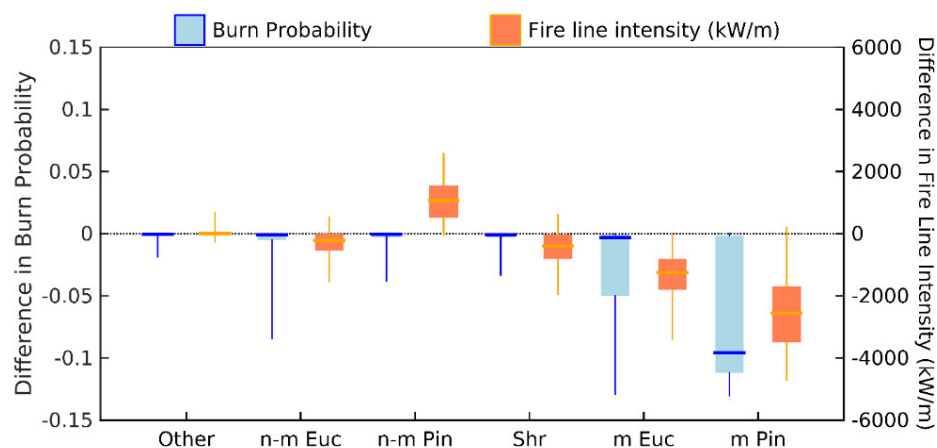


Figure 9. The impact of integrating fuel uncertainty in the estimated burn probability and fireline intensity for the main land use and cover types. Classes are non-managed (or untreated) eucalypt forest (n-m Euc); non-managed (or untreated) pine forest (n-m Pine); shrublands (Shr); managed (or treated) eucalypt forest (m Euc); managed (or treated) pine forest (m Pin). Difference in burn probability was calculated “with fuel uncertainty”–“without fuel uncertainty”.

The large decrease in fireline intensity in treated forests should be sufficient to allow a wildfire to be suppressed with heavy aircraft or to allow for its suppression only with ground resources. In shrublands, the low impact on burn probability, but a relevant decrease in intensity was due to the assumed model distribution, i.e., tall shrubs vs. a mixture of short and tall shrubs. For untreated forests, the impact was low because the assumed fuel distribution was only slightly different from the original, conservative fuel assumptions (i.e., models with high understory fuel loads). The increase in fireline intensity in untreated pine forests was a consequence of considering that besides the typical

“pine litter with understory vegetation” fuel model, these areas likely include also “tall shrubs”, a model with large fuel loads.

4.4. Impact of Fuel Management Scenarios on Wildfire Hazard

All fuel management scenarios consistently reduced wildfire hazard in Alvares. The total simulated burned area, used herein merely indicative terms, was reduced between 12.3% and 32.1% (Table 4) compared to the BAU option. Introducing different extents of the fuel break network resulted in a burned area reduction ranging from 15.9% to 28.6%. The impact of the randomly scattered fuel-treated areas in forest stands on the estimated burned area reduction was lower, ranging from 12.3% to 18.3%. The combination of both fuel management strategies led to a higher reduction in the burned area ranging from 20.8% to 32.1%. However, the reduction was smaller than that of the sum of the two separate effects.

Table 4. Variation in the total estimated burned area (%) compared to the BAU option. FBN stands for fuel break network.

	Same Management	Moderate Management	High Management
FBN 0\3	-	−12.3	−18.3
FBN 1\3	−15.9	−20.8	−24.8
FBN 3\3	−24.6	−24.1	−28.1
FBN 3\3	−28.6	−28.3	−32.1

Adding fuel breaks or increasing the fuel treatment area in forest stands produced very different impacts on burn probability decrease in the landscape (Figure 10). Fuel breaks led to higher burn probability decreases, particularly around their “area of influence”, as expected. On the other hand, an increasing fuel-treated area in forest stands randomly across the landscape led to a slightly lower burn probability decrease and more scattered across the landscape.

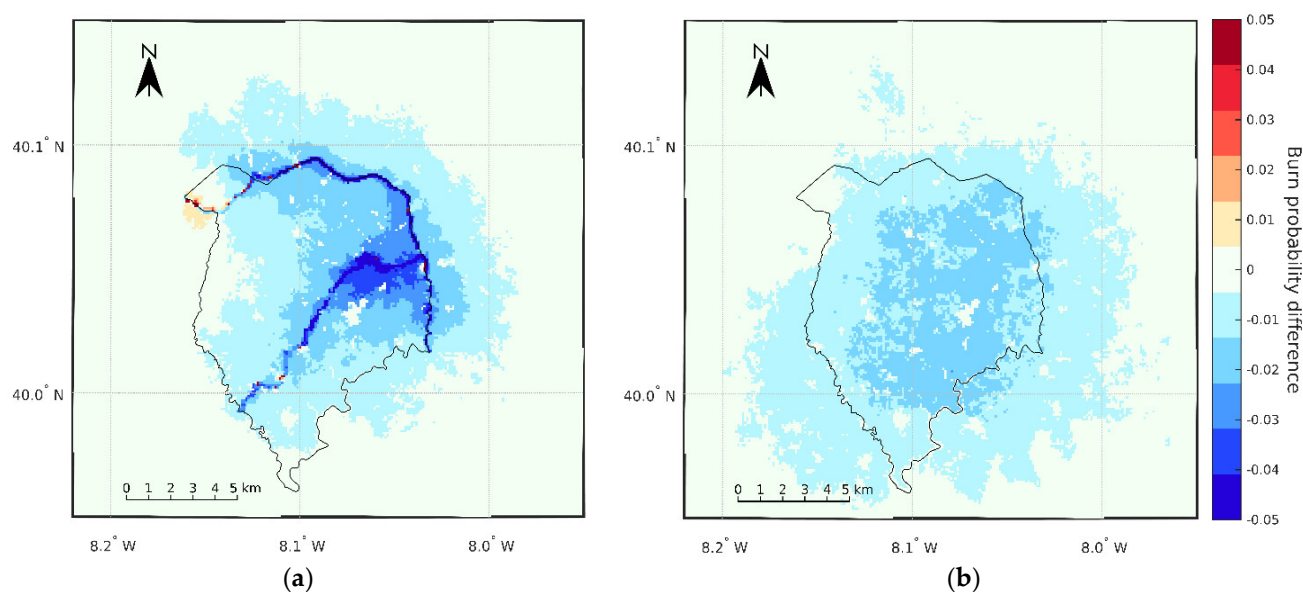


Figure 10. Impact of increased fuel management on estimated burn probability compared to the BAU option: (a) 1/3 of the fuel break network and (b) a moderate increase in the managed forest area.

All fuel management scenarios significantly decreased the frequency of very large wildfires inside the parish (Figure 11). Depending on the option considered, the frequency of wildfires larger than 5000 ha (half of the parish area) decreased between ~10% to ~40%. For the largest fire size class, the decrease varied between ~40% to ~90%. The fuel management scenarios that only considered fuel breaks led to larger decreases in wildfire extent compared to the scenarios based solely on the increase of treated forest area.

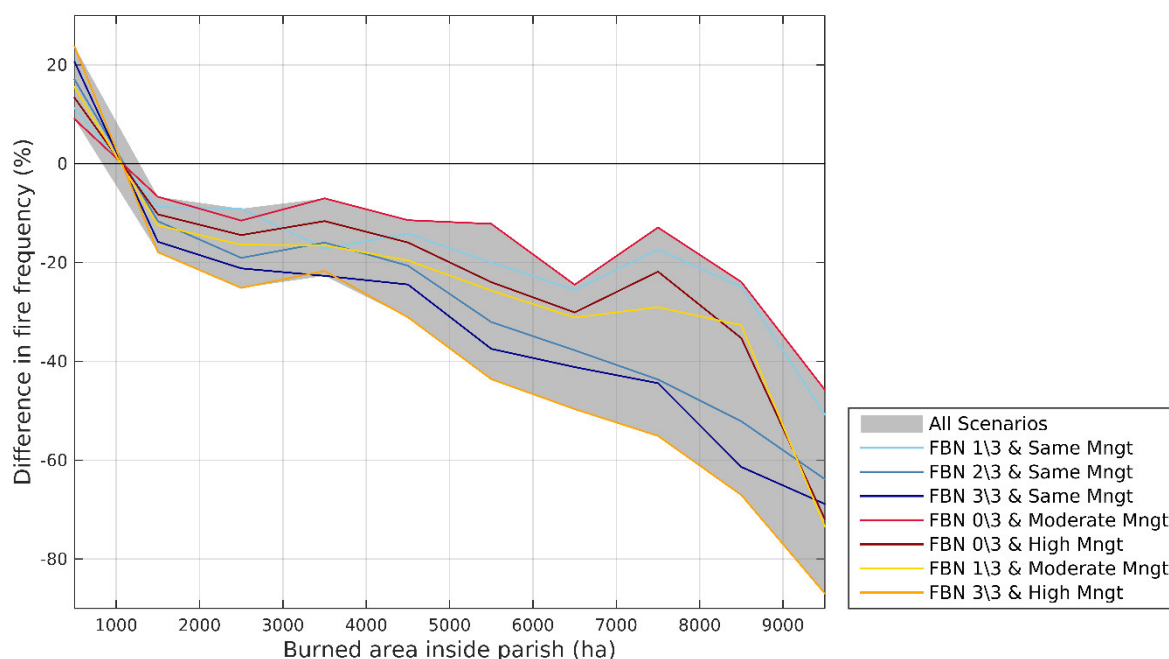


Figure 11. Impact of fuel management scenarios on the burned area extent inside the Alvares parish. “FBN” stands for fuel break network; “Mngt” stands for management.

As an indicative measure of treatment effectiveness, the total burned area reduction for each fuel management option was compared with the corresponding annual increase in the fuel treatment area (Figure 12; see Table 2). Results suggested that fuel breaks were slightly more effective than random stand-level fuel treatment (between 3 and 7% burned area reduction). Combining both approaches decreased the total burned area. However, it also decreased cost-effectiveness. As an example, applying the top priority fuel breaks (1/3 option) reduces around 15.9% of the burned area at the expense of managing an additional 50 ha year⁻¹. This is equivalent to a 0.3% burned area decrease per each additional ha annually treated. For the moderate treatment increase at the stand level, this value was lower and around 0.22%. When the top priority fuel breaks were combined with moderate treatment increase, for each added ha annually treated, the reduction decreased to 0.19%. Considering all treatment scenarios, on average, 0.22% of the burned area was reduced for each annually treated hectare ($r^2 = 0.92$). The reduction in the burned area was less pronounced above 50 ha year⁻¹ of the annual treated area.

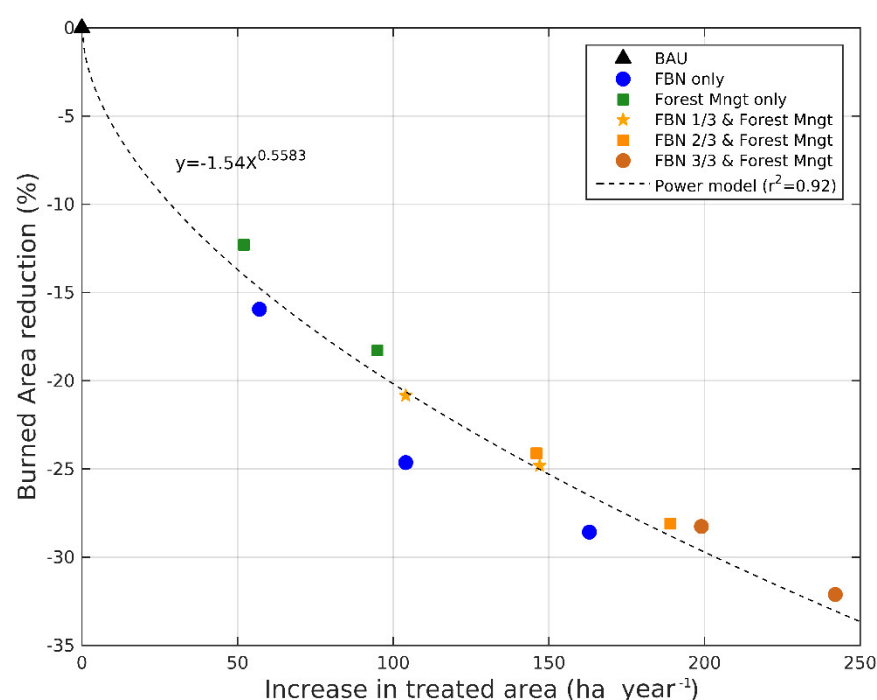


Figure 12. Comparison between burned area reduction (%) and increase in the area annually treated area (ha). The dashed line represents the power model adjusted to the data. X in the equation is the “increase in treated area (ha year⁻¹)” variable.

5. Discussion

This work introduced an innovative approach to estimate wildfire hazard at the landscape level by considering uncertainties and variability in the fuel distribution associated with different management strategies. FUNC-SIM proved very useful to understand the impact of relatively small changes in fuel treatment areas on wildfire hazard. It revealed important differences in estimated burn probability and fireline intensity, especially in treated forest stands, highlighting the suitability of the approach to effectively consider the impact of fuel management on wildfire hazard. It also provided a more realistic understanding of the impact of fuel breaks on wildfire hazard by considering that fuels in these areas change over time, rather than assuming time-invariant barriers [25]. The approach can be extremely useful to quantify how different efforts and spatial configurations of fuel treatment units can affect wildfire hazard. Additionally, it can also be used to uncover the role that different surface fuels (related to less fire-prone cover types, e.g., as determined by forest composition) have on wildfire hazard and risk assessment at the landscape level.

Model calibration results agreed well with historical data regarding fire size distribution and spatial patterns of fire activity. A slight underestimation occurred, particularly for smaller fire size classes, but is not expected to have a relevant impact on the overall results, considering that almost 90% of the burned area has been historically determined by very large wildfires (>1000 ha). The use of different ignition and fuel maps for the BAU option, as opposed to the baseline simulation, had very little impact on the estimated fire descriptors (not shown). This provided added confidence in FUNC-SIM’s ability to provide useful insights on the impact of different fuel management strategies on reducing wildfire hazard.

Nevertheless, the stochastic approach of FUNC-SIM still is affected by large uncertainties regarding both present and future fuel model distribution in the landscape. For example, results will be sensitive to the large uncertainties associated with the total forest area under fuel management and its frequency. Barreiro et al. (2021) [36] provided a rough estimate of 30% of managed eucalypt stand area based on information from the forest

owners association and a group of landowners. Santos et al. (2021) [34] estimated, for a sample of 221 owners, who managed 36% of the forest area, that 29% of the owners had treated fuels at least once in the last ten years. Both probably overestimate the area under frequent fuel treatment because there is much less information available regarding the spatial coverage of “absent” and “quasi-absent” FMAs. The lack of information on the location of individual properties and associated FMA introduced additional uncertainties. This is a common problem, not only in the Alvares parish but throughout most of rural Portugal and is aggravated by the fact that most of the area is private. The stochastic approach of FUNC-SIM should better cope with such uncertainties compared to more traditional approaches. Nevertheless, future work will benefit from having more detailed information on where how and when fuel is treated on the landscape, particularly for the larger-size properties.

If its landscape remains unchanged and similar to conditions prevailing before the 2017 wildfire, the Alvares parish will continue to suffer the consequences of frequent, very large and uncontrollable wildfires. The analysis indicated which areas are more likely to suffer very large and intense wildfires over the next 40 years. This can provide insights on which areas are more vulnerable and require priority efforts in the near future, for example, to protect villages with very high wildfire risk [37]. These analyses also showed that wildfire transmission is an important problem in Alvares, as it also has been shown for other areas of the country (e.g., [25]). Results strongly suggest that areas contiguous to the northern border of the parish are an important risk. Thus, treating fuels to reduce wildfire hazard should go beyond the limits of the parish and need to be planned and implemented over a broad area.

As expected, results suggest that the fuel management strategies may lead to relevant decreases in wildfire intensity, burn probability and frequency of large wildfires. Even with minor increases in the fuel treatment area, either through fuel breaks or in scattered forest stands, the impacts can be relevant. These results indicate that it is very important to increase the fuel treatment area in an under-managed landscape, such as Alvares. For example, combining the lowest FBN priority with a moderate increase in the area treated in forest stands (FB 1/3 and Moderate Mngt) reduced the total simulated burned area by 20.8% and reduced the probability of wildfires larger than 5000 ha between 20% to 70%.

Considering the two fuel management strategies, results point to a slightly higher impact of fuel breaks on reducing wildfire exposure, particularly in their “area of influence”. Some considerations are warranted. First, results are highly dependent on the fuel distribution that was assumed for fuel breaks. We tested a different distribution, assuming a higher probability of a wildfire stopping in the fuel breaks (i.e., non-burnable), and it nearly doubled the total burned area reduction. The additional effectiveness will depend on how firefighters use fuel breaks to suppress wildfires. In this respect, our results are a worst-case scenario, i.e., no fire suppression takes place in the fuel breaks. Conversely, spotting was also not simulated and can significantly reduce fuel break effectiveness, particularly in areas with high fire intensity and/or vertical continuity, typical of unmanaged eucalypt and pine stands. Comparison with the empirically determined return for effort of fuel treatments in eucalypt landscapes, where spotting is a relevant fire spread mechanism, suggests our results could be optimistic [53]. Finally, a simulation-based analysis is needed to complement the expert knowledge used in defining the priority segments of the fuel break network. This analysis should consider the complementary effect of different segments and other fuel management strategies.

Any fuel management strategy should be analyzed in terms of its effectiveness. Results suggest that the linear fuel break strategy seems to be more effective than random and scattered areal fuel treatments, particularly the “top priority” part of the network (FB 1\3). These results were expected considering that (i) the main purpose of fuel breaks is to reduce burned area and (ii) the fuel break locations were determined using expert knowledge and were not randomly dispersed over the landscape. Still, expert knowledge is subjective, and this stresses the necessity of identifying the optimal treatment locations

at the landscape level [27,28,54], possibly combining different strategies to improve the effectiveness of both linear and area-wide fuel treatments. Additionally, the annual increases in the managed area are in the same order of magnitude as the annual decreases in burned areas [46] for FBN 1\3 and 2\3 and a moderate increase in forest management. This suggests that the effectiveness of fuel management scenarios needs to be carefully evaluated, using a holistic and integrated approach, which can be separated into two main aspects: (1) moving beyond the concept of relying on burned area alone as an indicator of wildfire impact [16]; (2) taking into account the direct and indirect impacts of fuel management strategies on the safety of people and assets [37], wildfire costs [34] and economic revenues [36].

Overall, the approach presented here has the necessary flexibility to integrate uncertainties associated with fuels and estimate wildfire hazard in other areas of Portugal, as well as in other Mediterranean areas. The detailed forest management approaches and associated fuel distributions for eucalypt stands cover a wide range of possibilities and can be applied to a large extent of the country. The fuel distributions for shrublands would need to be adapted to the regional characteristics, for example, separating Atlantic from Mediterranean species. For pine forests, more information is necessary regarding the existing forest management approaches and the fuel distribution in areas with natural regeneration (e.g., understand the fuel dynamics over time) associated with wildfires that occurred in the last decades. Regarding fuel breaks, the approach presented can be applied to most of the Portuguese territory, easily adapted to cover additional variations (e.g., different treatment frequencies) or applied to other fuel management strategies. Regarding the results presented, results should be valid at least for forest-dominated landscapes, with a large fraction of eucalypt forests, rugged terrain and a short fire cycle. This definition covers a large extent of center Portugal, the most fire-prone area of the country.

6. Conclusions

In the aftermath of the extreme 2017 wildfire season in Portugal, it is crucial to find smart and effective solutions to create fire-resilient landscapes. In this work, we developed a tool (FUNC-SIM) to evaluate how different fuel treatment strategies may affect wildfire hazard in the Alvares parish in the next 40 years. We followed an innovative approach based on fuel distributions and stochastic simulation that provides a more realistic approach to integrate different fuel treatment strategies.

If the landscape remains unchanged, Alvares will continue to be affected by frequent, large wildfires, with larger probabilities estimated to occur in the north, northeast and center-east areas of the parish. They will be associated with fireline intensities that require aerial resources and sometimes are beyond suppression capabilities. Increasing fuel treatment area in the parish is critical to reducing exposure, intensity and the likelihood of very large wildfires. Fuel treatment scenarios decreased burned area between 12.1 and 31.2% and significantly reduced the likelihood of very large wildfires affecting the parish, for example, 10% to 40% for fire sizes larger than 5000 ha, depending on the scenario.

About 8% of the eucalypt forest area in Alvares is treated annually, and depending on the fuel treatment scenario, this area increased between 1% and 4.6%, decreasing the total burned area between 12.1 and 31.2%, respectively. On average, as an indicative figure, simulated burned area decreased 0.22% per ha treated, and fuel treatment cost-effectiveness decreased with increasing area treated. Overall, both fuel treatment strategies can effectively reduce wildfire hazard and be part of a larger, holistic and integrated plan to reduce the vulnerability of the Alvares parish to wildfires in the future.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This appendix describes additional details regarding the data used in FUNC-SIM to simulate wildfire hazard in the Alvares parish. The wind direction and intensity are shown in Figure A1. The distribution of the fuel treatment area size is shown in Figure A2. The distributions of the fuel models for the several forest management approaches identified in the study region are shown in Tables A1 and A2. The latter was created based on expert knowledge and information provided by the forest owners association, industrial companies and non-industrial landowners.

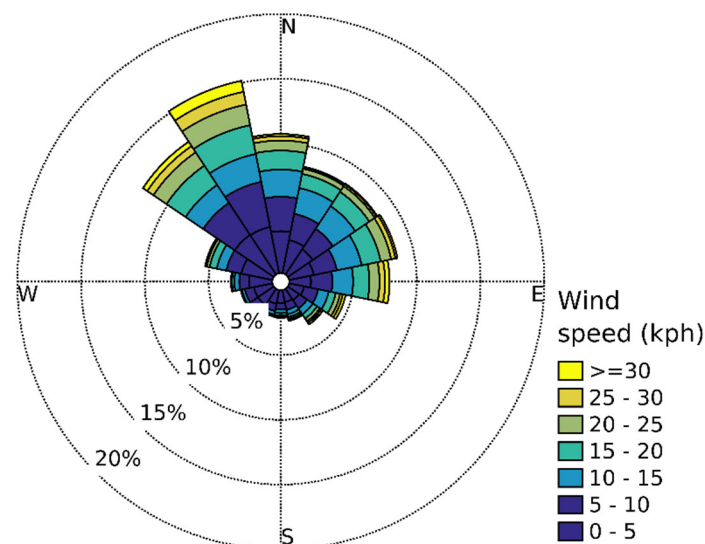


Figure A1. Sampled wind direction and wind intensity distribution used as input in FUNC-SIM.

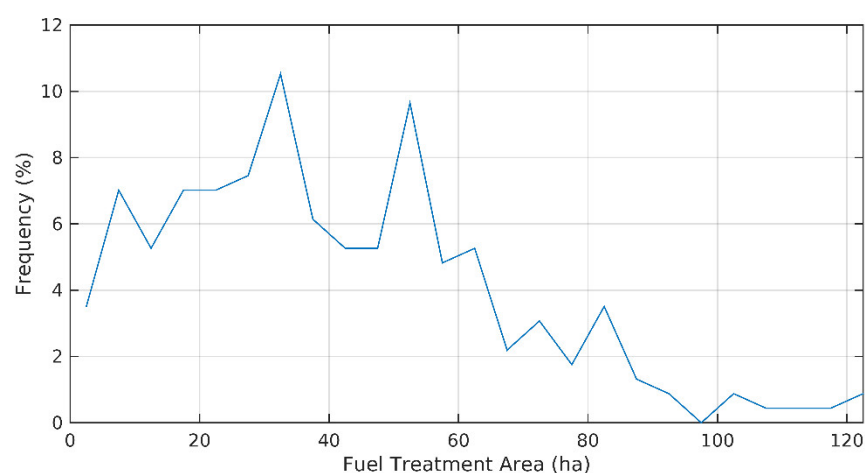


Figure A2. Fuel treatment area size distribution related to the increase in forest stand management strategy.

Table A1. Fuel model distribution across time for three eucalypt rotations: industrial FMA and non-industrial “active” and “semi-active” FMA. Acronyms are explained in Table 1 of the main text.

Rotation	Year	Industrial		Non-Industrial "Active"		Non-Industrial "Semi-active"	
		Fuel Model		Fuel Model		Fuel Model	
1	1		NA		NA		NA
	2	*	NA	*	NA		NA
	3		NA		NA		NA
	4	*	M-EUCd	*	M-EUCd	*	M-EUCd
	5		M-EUCd		M-EUCd		M-EUCd
	6		F-EUC	*	M-EUCd		F-EUC
	7	*	M-EUCd		F-EUC		F-EUC
	8		F-EUC		F-EUC		F-EUC
	9		F-EUC		F-EUC		M-EUC
	10		F-EUC		M-EUC		M-EUC
	11		M-EUC		M-EUC		M-EUC
	12		M-EUC		M-EUC		M-EUC
2	1		NFFL11		NFFL11		NFFL11
	2		NFFL11		NFFL11		NFFL11
	3		NFFL11		NFFL11		NFFL11
	4		M-EUC	*	M-EUCd	*	M-EUCd
	5	*	M-EUCd		M-EUCd		M-EUCd
	6		M-EUCd		F-EUC		F-EUC
	7	*	M-EUCd		F-EUC		F-EUC
	8		F-EUC		F-EUC		F-EUC
	9		F-EUC		M-EUC		M-EUC
	10		F-EUC		M-EUC		M-EUC
	11		M-EUC		M-EUC		M-EUC
	12		M-EUC		M-EUC		M-EUC
3	1		NFFL11		NFFL11		NFFL11
	2		NFFL11		NFFL11		NFFL11
	3		NFFL11		NFFL11		NFFL11

	4	M-EUC	*	M-EUCd	*	M-EUCd
	5	* M-EUCd		M-EUCd		M-EUCd
	6	M-EUCd		F-EUC		F-EUC
	7	* M-EUCd		F-EUC		F-EUC
	8	F-EUC		F-EUC		F-EUC
	9	F-EUC		M-EUC		M-EUC
	10	F-EUC		M-EUC		M-EUC
	11	M-EUC		M-EUC		M-EUC
	12	M-EUC		M-EUC		M-EUC

* year when it is assumed that understory fuel treatment occurs.

Table A2. Fuel model distribution across time for three eucalypt rotations: industrial FMA and non-industrial “quasi-absent” and “absent” FMA. Acronyms are explained in Table 1 of the main text.

		Non-Industrial "Quasi-Absent"		Non-Industrial "Absent"	
Rotation	Year	Fuel Model		Fuel Model	
1	1		M-EUCd		M-EUC
	2	*	M-EUCd		M-EUC
	3		M-EUC		M-EUC
	4	*	M-EUC	*	M-EUC
	5		M-EUC		M-EUC
	6	*	M-EUC		M-EUC
	7		M-EUC		M-EUC
	8		M-EUC		M-EUC
	9		M-EUC		M-EUC
	10		M-EUC		M-EUC
2	1		NFFL11		M-EUC
	2		NFFL11		M-EUC
	3		NFFL11		M-EUC
	4	*	M-EUC	*	M-EUC
	5		M-EUC		M-EUC
	6		M-EUC		M-EUC
	7		M-EUC		M-EUC
	8		M-EUC		M-EUC
	9		M-EUC		M-EUC
	10		M-EUC		M-EUC
3	1		11		M-EUC
	2		11		M-EUC
	3		11		M-EUC
	4	*	M-EUC	*	M-EUC
	5		M-EUC		M-EUC
	6		M-EUC		M-EUC
	7		M-EUC		M-EUC
	8		M-EUC		M-EUC
	9		M-EUC		M-EUC
	10		M-EUC		M-EUC

* year when it is assumed that understory fuel treatment occurs.

Appendix B

This appendix provides additional information regarding the model calibration results, particularly regarding the fireshed estimation (Figure A3) and the impact of integrating uncertainty in fuel model distribution on simulated fire size (Figure A4).

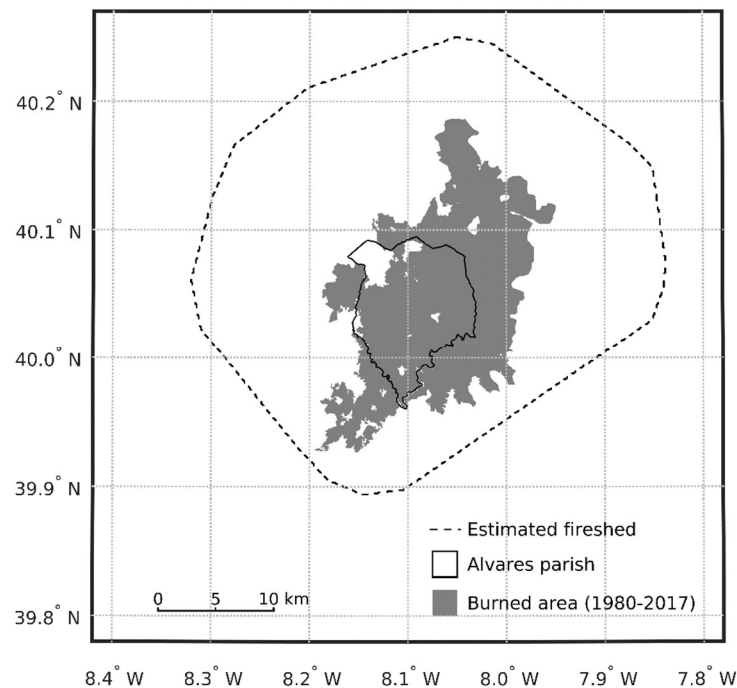


Figure A3. Estimated fireshed (historical calibration period) and the observed wildfire footprint between 1980 and 2017.

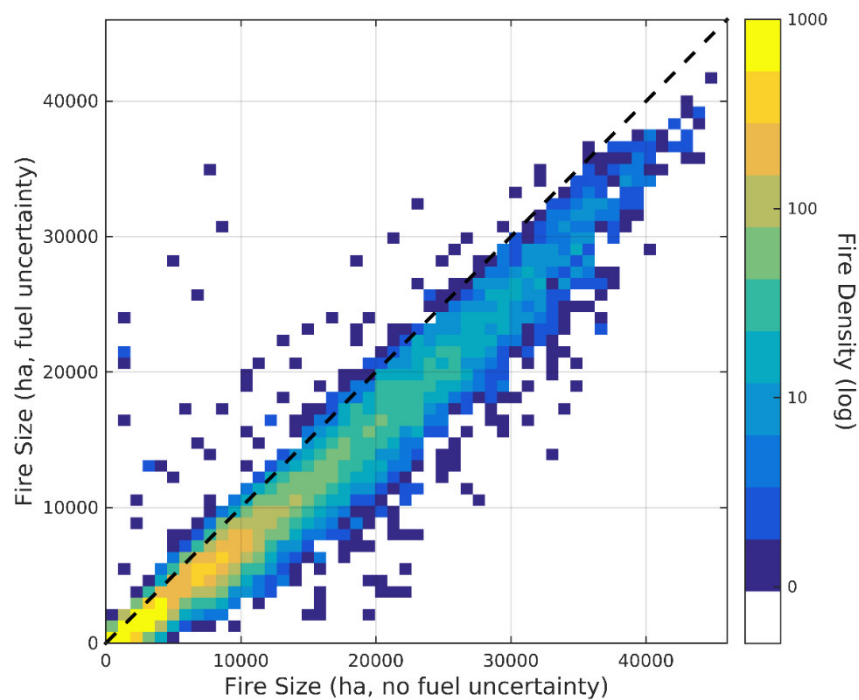


Figure A4. Comparison between simulated fire size with and without integrating uncertainty in fuels. Each pixel reflects the number of simulated wildfires (in logarithmic scale). The dashed line is the 1:1 line.

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