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Article

Understanding the impact of different landscape-level fuel management strategies on wildfire hazard

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Abstract: The disastrous 2017 fire season in Portugal lead to widespread recognition of the need for a paradigm shift in forest and fire management. We focused our study on Alvares, a parish in central Portugal which had 60% of its area burned in 2017, with a large record of historical. We evaluated how different fuel treatment strategies can reduce wildfire hazard in Alvares, through i) a fuel break network with different priorities and ii) random fuel treatments resulting from stand-level management intensification. To assess this, we developed a stochastic fire 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 fire line intensities. The different fuel treatment scenarios decreased burned area between 12.1-31.2%, resulting from 1%-4.6% increases in annual treatment area, and reduced 10%-40% the likelihood of wildfires larger than 5000 ha. On average, simulated burned area decreased 0.22% per each ha treated, and 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: wildfire; hazard; modelling; stochastic; fuel treatment; fuel breaks; forest management

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 characterized 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 extreme and frequent fire behavior in the future [14], setting the conditions for more severe fire seasons, such as that one of 2017.

Effective strategies are necessary to reduce the likelihood of severe fire seasons in the future are necessary. 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 fire hazard reduction tool, landscape fuel management alternatives should be considered as part of a holistic and integrated approach, interconnecting the several actors and phases of the complex wildfire problem [16–18].

Science can contribute to the necessary change by providing sound knowledge and tools for more effective landscape fuel management, 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

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also proven useful to quantify the potential impact of climate change on wildfire exposure [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. 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 ageing [32], abandonment of agricultural lands and expansion of forest and shrubland area [16], and increasing frequency of droughts and heat waves 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 lead to undermanagement of forests and pasture areas. These environmental and socio-economic factors have contributed to the development of a very hazardous 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, contributing to support the necessary change in the forest management paradigm and the development of fire-resilient landscapes [35]. Here, we evaluated how different fuel treatment strategies can reduce wildfire hazard in Alvares. Two main strategies were analyzed: shaded 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. Our objective was to understand how these fuel management scenarios can change future wildfire hazard, in comparison with 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, as well as quantifying 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 [36]. The summer months (July and August) are usually dry and receive, on average, around 15-20mm 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% of forest area [35], to a forest-dominated landscape (ca. 90%), composed mainly of Eucalyptus globulus Labill. (Tasmanian blue gum and shinning gum, hereafter eucalypt) (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 used for production objectives, and eucalypt mainly for the pulp and paper industry, pine is mainly used for timber. Similar to 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 [37,38]. More than 96% of the lands is privately owned, by more than 3000 landowners, including two paper industry companies [35].

The Alvares parish has 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 4a). The last very large wildfire occurred in June 2017 and was the most destructive on record, burning around 60% of the parish area.

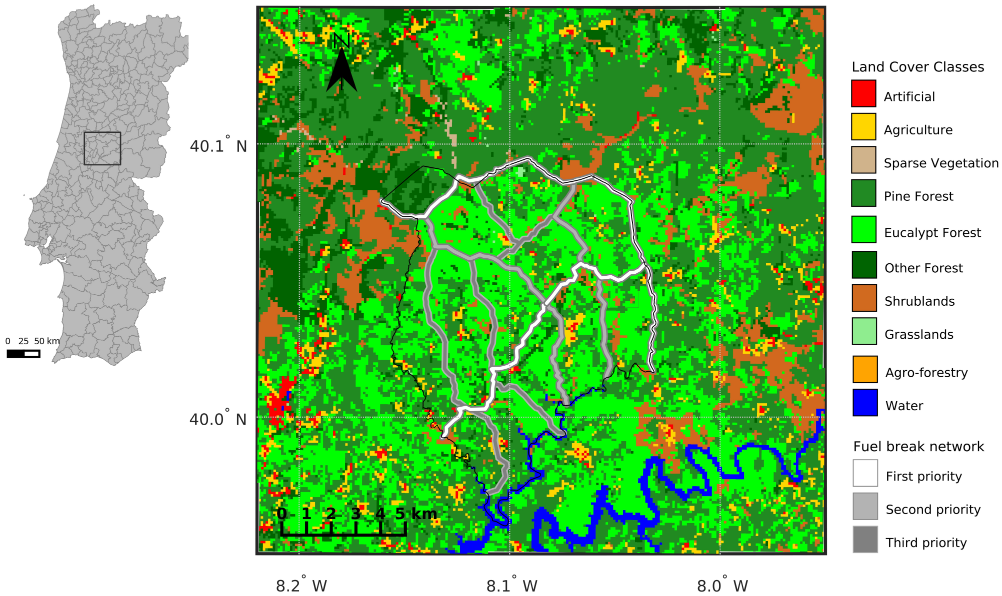

Figure 1. Study region: Land cover and spatial context. Land cover classes derived from the Portuguese 2015 land use map; Fuel break network design is explained in section 3.2.

3. Materials and Methods

3.1. Fire Spread Simulation

3.1.1. Data and modelling 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 [39]. The modelling 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 55x55 km window centered on the Alvares parish, to take into account wildfire transmission across the neighboring parishes and municipalities. The grid resolution was set to 100 m.

The dates of the historical large wildfires in the study region between 1980 and 2017 were extracted from the Portuguese Forest Service fire database [40]. Data prior to 1980 was not available. Temperature, relative humidity, and wind data were derived from WRF 4km-resolution forecasts [41] using 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 [42] 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 (FigureS1 - 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 of 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 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 [43]) 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) [44]. The fuel maps have large uncertainties due to several reasons, namely errors in the base land cover map, the correspondence procedure, and due to fuel temporal dynamics (e.g.[45]). For these reasons, the fuels in the landscape were represented using a stochastic approach. 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) to eucalypt plantations vary widely and are described in detail in Barreiro et al. [46]. Around 23% of the eucalypt area was industrial, and the remaining 77% was from non-industrial landowners, that were 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 S1 and S2 - Appendix A) that were translated into probabilities (Figure 2). 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 [46]) to estimate the fuel model probability.

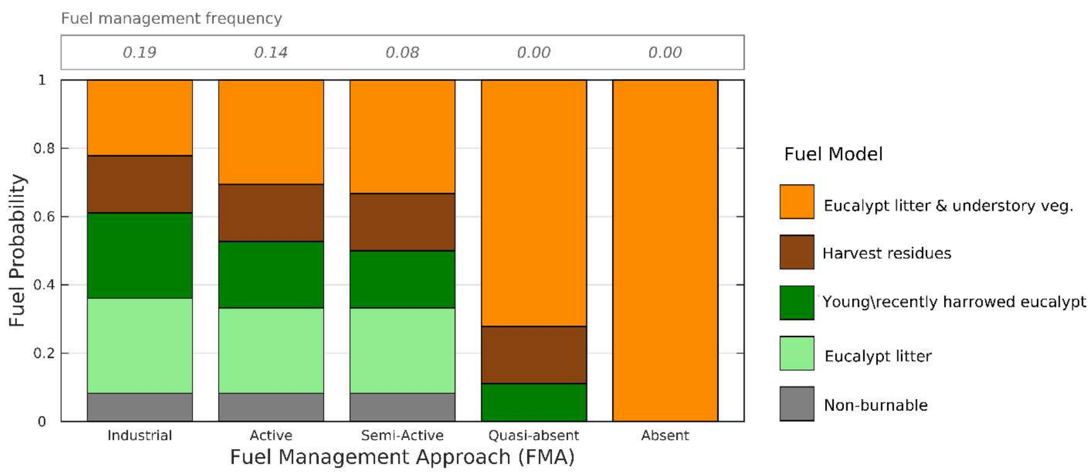

Figure 2. Fuel model probability for each forest management approach. Fuel management frequency was calculated as the fraction of harrowing operations in 40 years.

Much less information was available for pine stands and therefore the fuel model distribution was only based in two FMA: industrial and non-industrial. The fuel model distribution in shrublands was defined based on the knowledge obtained in previous studies [10], since FMA do 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 from 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 [48]. Due to lack of information, canopy fuel variables were set constant based on expert knowledge. The thousands of simulated wildfires were

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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.

Fire line intensity (FLI) was also estimated and adopted as an indicative measure of fire resistance to control. For each pixel, the percentile 90 of all FLI values was calculated and reclassified according to Alexander and Lanoville (1989) [49]. The top two classes were merged into a unique "Very High & 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 [47]

3.1.1. 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. Therefore, fuel model distributions were defined based on equal proportions of the fuel maps resulting from the correspondence with the Portuguese Land Use and Cover maps for 1990 and 2015. 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 landscape-level: i) the implementation of a fuel break network (linear strategy), and ii) the dispersed random increase in treated forest area, at 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. [50]).

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 [25,51]. 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: first priority, corresponding to 1/3

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of the total FBN extent; 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 will be managed, on average, every five years to keep fuel loadings 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 with the forest association and landowners [46], and inquiries [34], 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 encompasses a wide range of different treatment frequencies. It is estimated that currently around 420 ha are treated annually at parish level, of which more than half (ca. 242 ha) are done by industrial owners. In relative terms, this while industry treat 19% of their eucalypt forest stands, 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 area 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 amount of available information [34]. The increases in managed area were attained by replacing lower by higher intensity FMA, in different proportions depending on whether the increase was moderate or high [46]. Hence, it was assumed that the fraction of active landowners increases at the expense of a decrease of 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 managed area were integrated are described in section 2.4.

The effort in implementing the FBN was divided in four levels: none (equivalent to BAU), top priority, medium and top priority, and the entire network. The increase in the managed forest stand area was divided in three levels: same level of treatment (assumed has the same as in 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 in the potential future distribution of wildfires over 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 land cover map of 2015 was used to create the reference fuel map. In industry properties the reported land cover was used instead, and 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 distribution of patch size ranged between 1ha to 119 ha, with an average size of 38 ha (Figure S2 – Appendix B). This value was significantly larger than average property size (average of 0.5ha), 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 analyzed 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 intervened area was unburnable, and that in the following years grass and shrub fuels built up until fuel reduction operation is 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 [46]. 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 [47]

The simulation for the BAU option was run 100000 times. The fireshed (e.g. [26]), was estimated as the convex area for which a potential ignition can lead to a wildfire that will 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 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 relation between the increase in annual treated area and the reduction of total estimated burned area, as a rough indicator of effectiveness. Comparisons were made by analyzing relative changes in these indicators when compared with 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 3). 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 a slightly underestimated, and for wildfires smaller than 1000 ha where there was a clear overestimation.

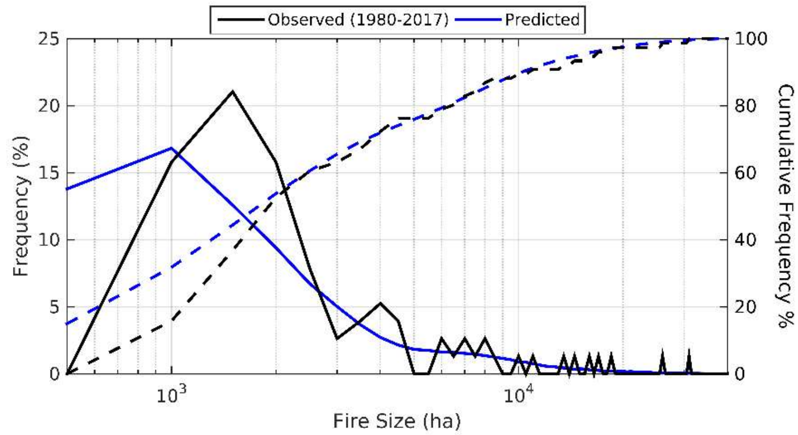
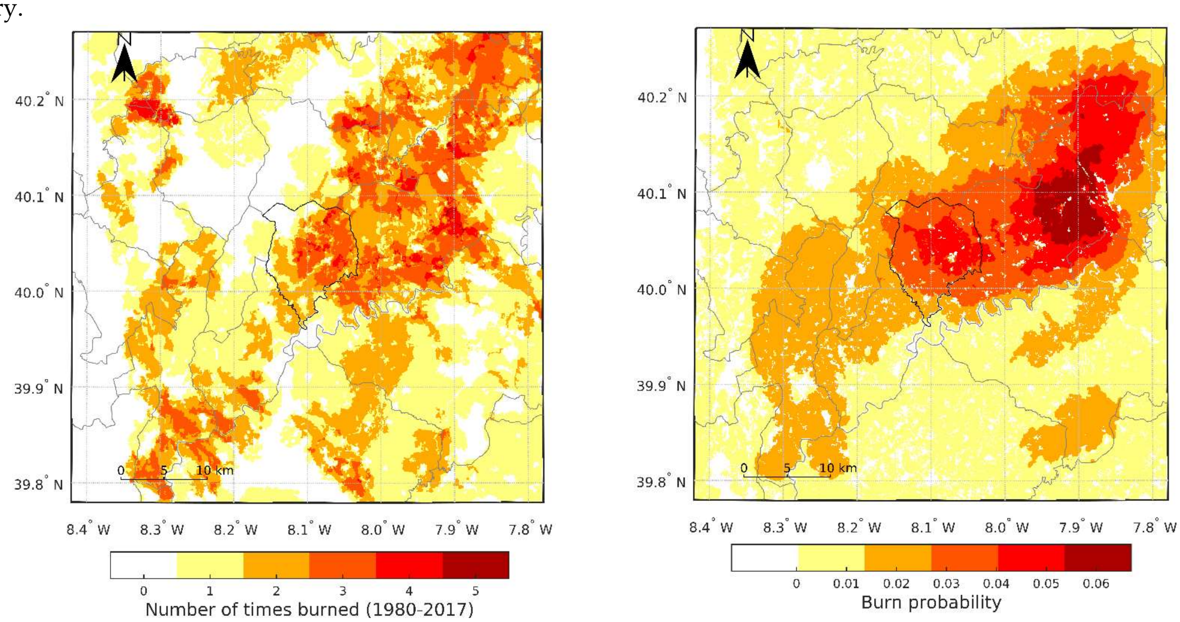


Figure 3. Comparison between observed and predicted fire size in a logarithmic scale. Filled lines represent frequency and dashed lines cumulative frequency (both in %).

The spatial patterns of observed wildfire frequency since 1980 (Figure 4a) were very similar to the estimated burn probability in Alvares, and surrounding areas (Figure 4b). 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.



(**a**) (**b**)

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

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

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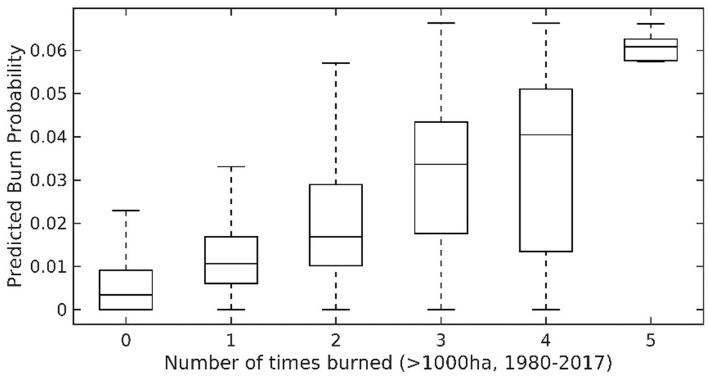

Figure 5. Comparison between the spatial distribution of observed frequency of very large wildfires between 1980 and 2017 and predicted burn probability.

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

The calibrated fire modelling system was used to estimate wildfire hazard in the Alvares parish for the BAU option. Assuming that the landscape remains unchanged, the 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 4). Most of the parish had moderate (21%) or high (63%) estimated fire line intensity. Very high and extreme fire line intensity occupied 8.6% of the parish area. In general, higher intensity was coincident with large contiguous shrubland areas, while lower intensities occurred in managed forest areas and short-needle coniferous forest (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.

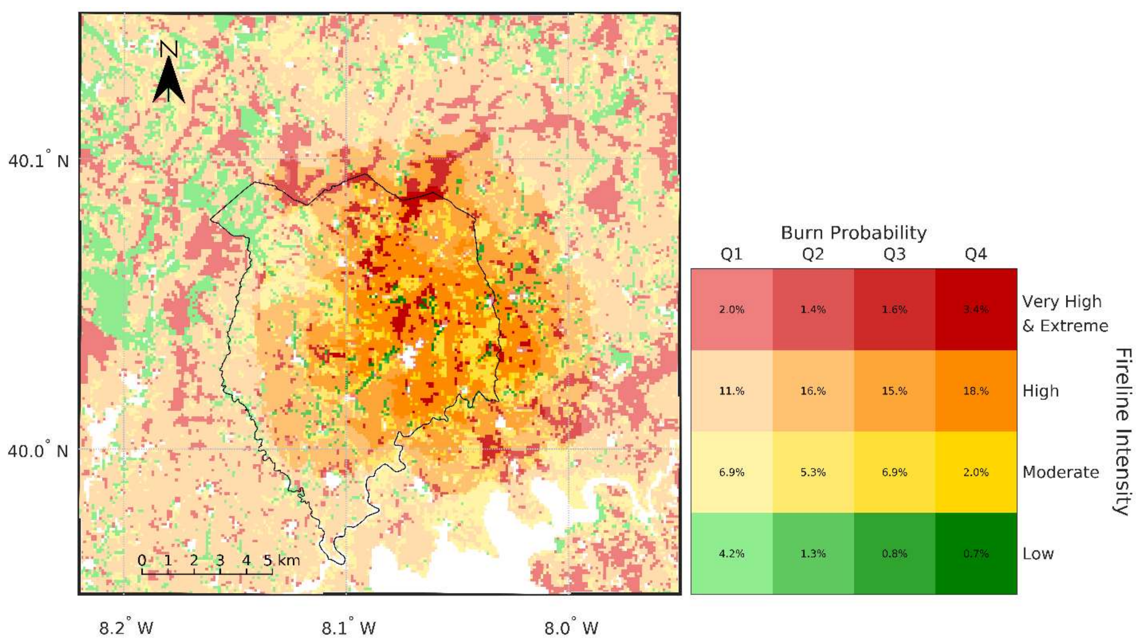

Figure 6. Combination of simulated burn probability and fireline intensity in the Alvares parish and close surroundings. Q1, Q2, Q3 and Q4 are the quartiles of burn probability.

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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 S1 – Appendix A). Historical and BAU estimated fireshed were similar and contained all the burned area footprint during the 1980-2017 period (see Figure S3 - Appendix B).

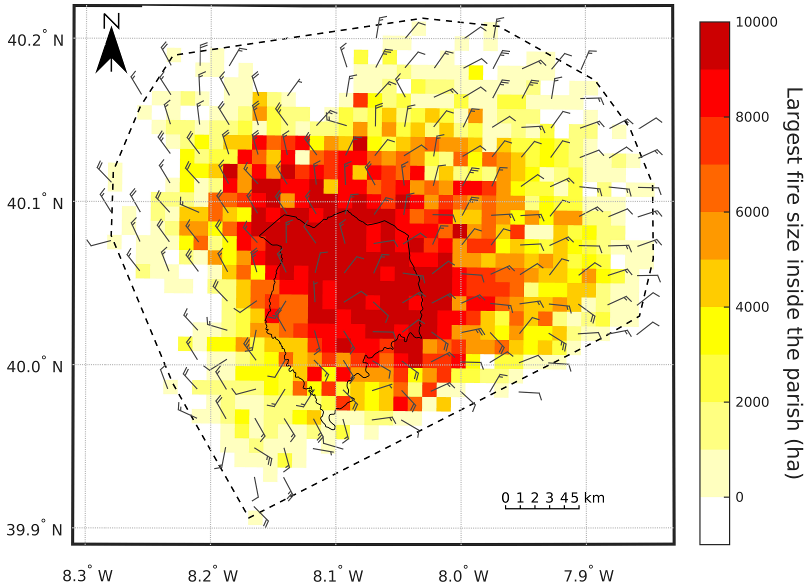

Figure 7. Largest burned area extent (ha) inside the Alvares parish from wildfires originating at each pixel location, and respective dominant wind direction (BAU option). The dashed line represents the fireshed.

The fireshed extent and shape suggests 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 exception of the south/southwestern part, have the potential to generate wildfires that can burn over 80% of the Alvares parish. In the vicinity of 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 S4 - 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.

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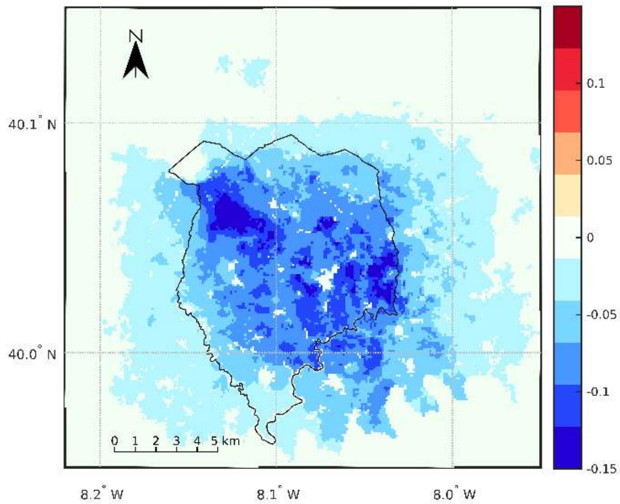

Figure 8. Impact of integrating fuel uncertainty in the spatial distribution of estimated burn probability. The color bar shows the difference in burn probability calculated as "with uncertainty" – "without uncertainty".

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.

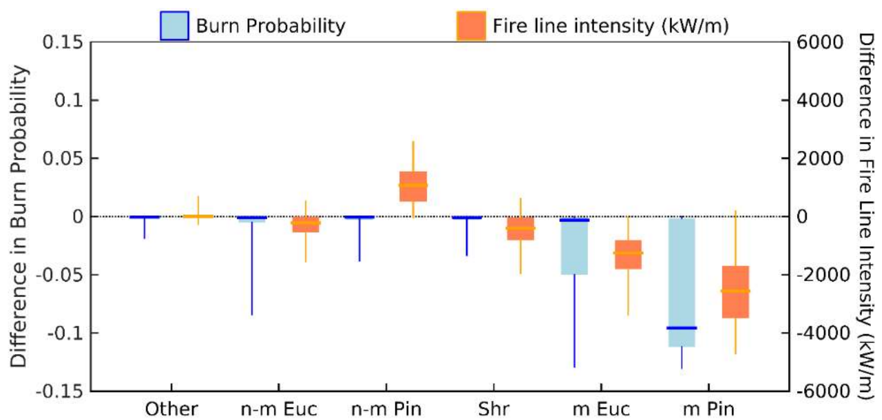

Figure 9. The impact of integrating fuel uncertainty in the estimated burn probability and fireline intensity for the main land use and cover types. Classes are non-managed (or untreated) eucalypt forest (n-m Euc); non-managed (or untreated) pine forest (n-m Pine); shrublands (Shr); managed (or treated) 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 forest should be sufficient to allow a wildfire to be suppressed with heavy aircrafts or to allow for its suppression only with ground resources. In shrublands, the low impact on burn probability but 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 forest, 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 forest 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 load.

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 here in merely indicative terms, was reduced between 12.3% and 32.1% (Table 4) when compared with 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

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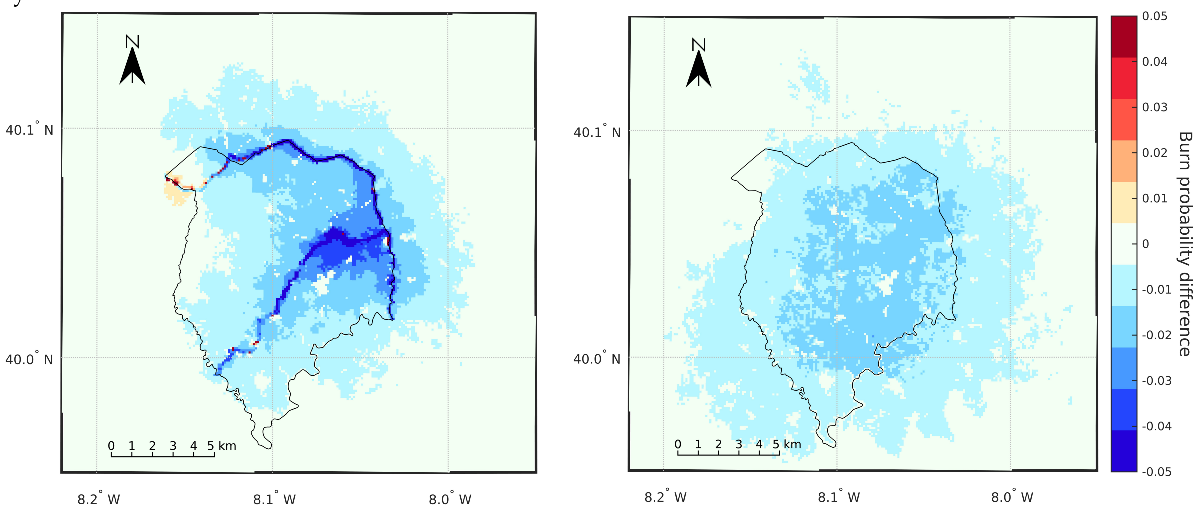
was lower, ranging from 12.3% to 18.3%. The combination of both fuel management strategies led to a higher reduction in burned area ranging from 20.8% to 32.1%. However, the reduction was smaller than that of the sum of the two separate effects.

Table 4. Variation in total estimated burned area (%), when compared with 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, increasing fuel-treated area in forest stands randomly across the landscape led to a slightly lower burn probability decrease, but more scattered across the parish and its vicinity.



(a) (b)

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

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

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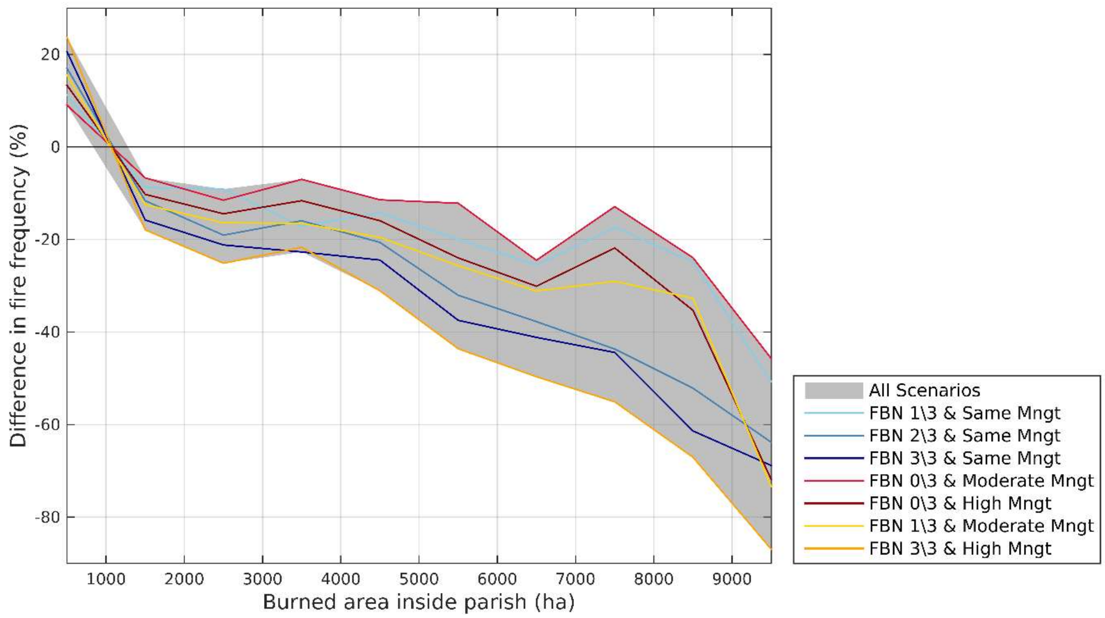

Figure 11. Impact of fuel management scenarios on the burned area extent inside the Alvares parish. 'FBN' stands for fuel break network and 'Mngt' stands for management.

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 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 total burned area, however, it also decreased effectiveness. As an example, applying the top priority fuel breaks (1/3 option) reduces around 15.9% of burned area at the expense of managing an additional 50ha year-1, equivalent to a 0.3% burned area decrease per each additional ha annually treated. For the moderate treatment increase, this value was 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 burned area was reduced for each annually treated hectare (r2=0.92). The reduction in burned area was more pronounced up to around 50 ha year-1 of annual treated area.

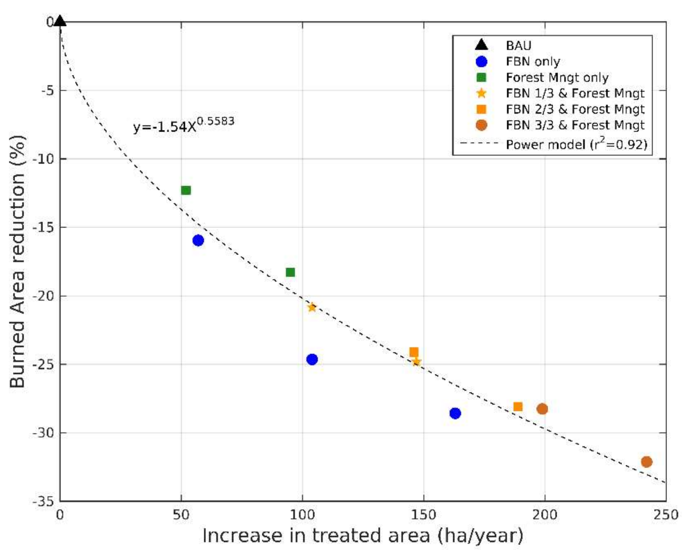

Figure 12. Comparison between burned area reduction (in %) and increase in the area annually treated area (in ha). The dashed line represents the power model adjusted to the data. X in the equation is the "increase in treated area (ha/year)" variable.

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5. Discussion

This work introduced an innovative approach to estimate wildfire hazard at the landscape level by taking into account 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 area 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 take into account 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 taking into account 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 have on 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, can have on wildfire hazard and risk assessment at landscape-level.

Model calibration results agreed well with historical data in terms of 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 most 90% the burned area has been historically determined by very large wildfires (>1000ha). The use of different ignition and fuel maps for the BAU option, in comparison with the baseline simulation, had very little impact on the estimated fire descriptors (not shown). This provided added confidence on 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) [46] provided a rough estimate of 30% of managed eucalypt stands 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 regarding the spatial coverage of 'absent' and 'quasi-absent' FMAs. The lack of information on the location of individual land owners' 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 when compared with 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 prior to 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 [50]. Analysis also showed that wildfire transmission is an important problem in Alvares, as it has also 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 needs to be planned and implemented over a broad area.

As expected, results suggest that the fuel management strategies can lead to relevant decreases in wildfire intensity, burn probability, and frequency of large wildfires. Even with minor increases in 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 such an under-managed landscape such as Alvares. For example, combining the lowest FBN priority with a moderate increase in area treated in forest stands (FB 1/3 & 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 to what extent fire fighters use fuel breaks to suppress wildfires, and 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

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the empirically determined return for effort of fuel treatments in eucalypt landscapes, where spotting is a relevant fire spread mechanism, suggests our results are 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 by nature 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 additional increases in managed area are in the same order of magnitude of the annual decreases in burned area [46] for FBN 1\3 and 2\3 and 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 decomposed in two main aspects: first, moving beyond the concept of relying on burned area alone as an indicator of wildfire impact [16]; second, taking into account the direct and indirect impacts of fuel management strategies on the safety of people and assets [50], wildfire costs [34] and economic revenues [46].

6. Conclusions

In the aftermath of the 2017 disastrous 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 could 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 very large wildfires, with larger probabilities estimated to occur in the north, northeast, and center-east areas of the parish, very often associated with fire line intensities that require aerial resources and sometimes are beyond suppression capability. Increasing fuel treatment area in the parish is critical to reduce 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 total burned area between 12.1 and 31.2%, respectively. On average, as an indicative figure, simulated burned area decreased 0.22% per each ha treated, and the fuel treatment effectiveness decreased with increasing area treated. Overall, both fuel treatment strategies considered can effectively reduce wildfire hazard and should 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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Supplementary Materials: Figure S1. Sampled wind direction and wind intensity distribution used as input in FUNC-SIM. Figure S2. Fuel treatment area size distribution related with the increase in forest stand management strategy. Table S1. Fuel model distribution across time for three eucalypt rotations: industrial FMA, and non-industrial 'active' and 'semi-active' FMA. Table S2. Fuel model distribution across time for three eucalypt rotations: industrial FMA, and non-industrial 'quasi-absent' and 'absent' FMA. Figure S3. Estimated fireshed (historical period – calibration) and the observed wildfire footprint between 1980 and 2017. Figure S4. Comparison between simulated fire size with and without integrating uncertainty in fuels. Each pixel reflects the number of simulated wildfires (in logarithmic scale).

Author Contributions: Conceptualization, A.B. and J.M.C.P.; methodology, A.B., A.S., P.F., J.P.; formal analysis, A.B.; investigation, A.B.; writing—original draft preparation, A.B.; writing—review and editing, A.B., A.S., P.F., J.P., J.M.C.P.; funding acquisition, J.M.C.P. All authors have read and agreed to the published version of the manuscript."

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Conflicts of Interest: The authors declare no conflict 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 is shown in Figure S1. The distribution of the fuel treatment area size is shown in Figure S2. The distribution of the fuel models for the several forest management approaches identified in the study region are shown in Tables S1 and S2. The latter were created based on expert knowledge and information provided by the forest owners association, industrial companies, and non-industrial land owners.

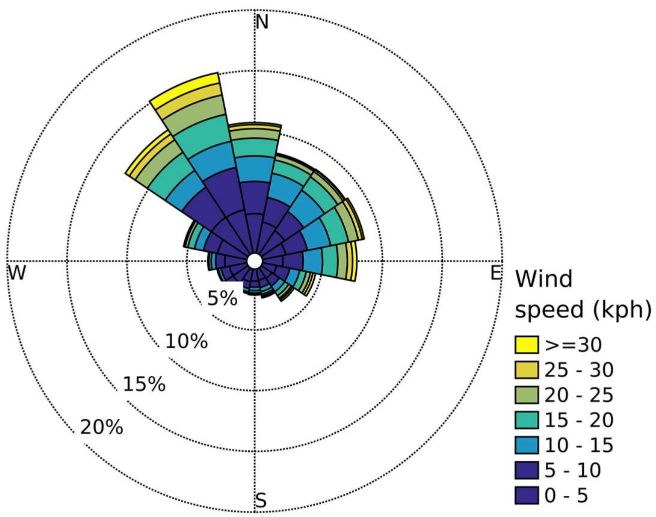

Figure S1. Sampled wind direction and wind intensity distribution used as input in FUNC-SIM.

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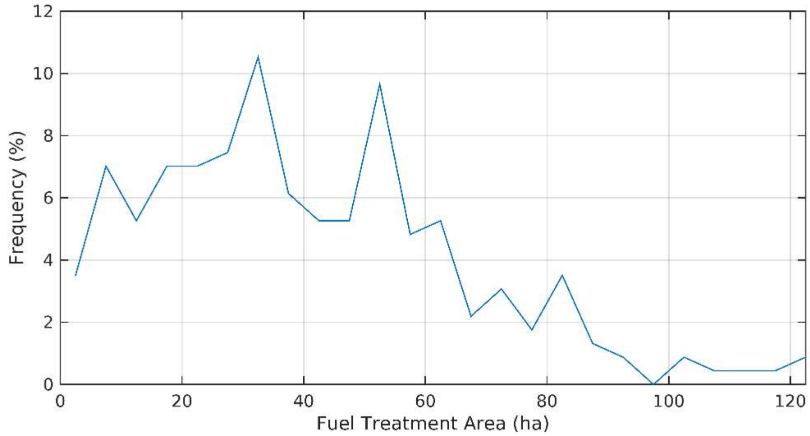

Figure S2. Fuel treatment area size distribution related with the increase in forest stand management strategy.

Table S1. 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.

			Industrial		Non-industrial 'active'		Non-industrial 'semi-active'
Rotation	**Year**		**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

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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 2. 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.

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Appendix B

This appendix provides additional information regarding the results of the model calibration, in particular regarding the fireshed estimation (Figure S3), and regarding the impact of integrating uncertainty in fuel model distribution in simulated fire size (Figure S4).

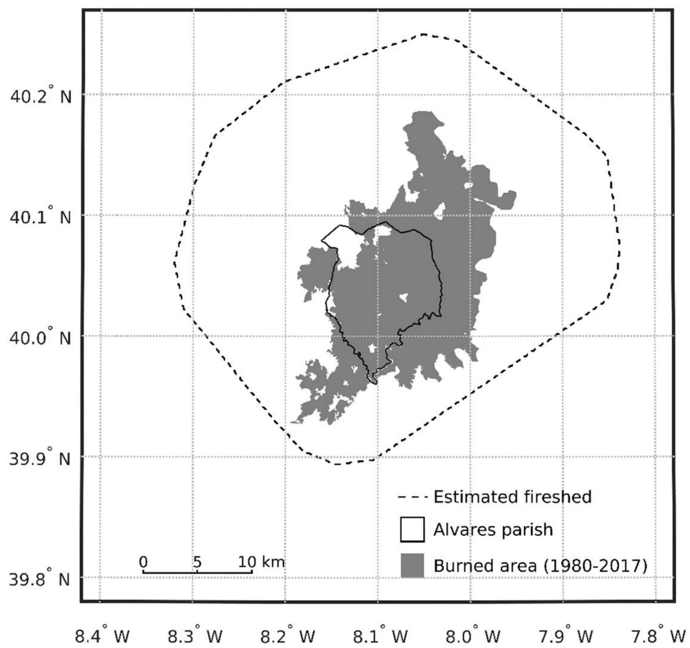

Figure S3. Estimated fireshed (historical period – calibration) and the observed wildfire footprint between 1980 and 2017.

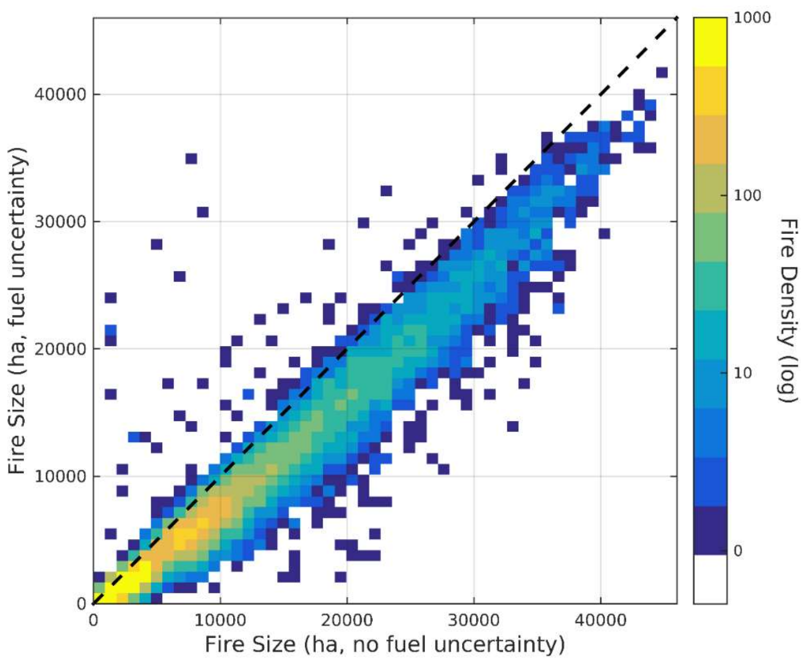

Figure S4. Comparison between simulated fire size with and without integrating uncertainty in fuels. Each pixel reflects the number of simulated wildfires (in logarithmic scale). The dashed line is the 1:1 line.

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