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ORIGINAL PAPER

Assessing the effects of alternative fuel treatments to reduce wildfire exposure

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Abstract Effective landscape-scale fuel management strategies are essential for reducing wildfire risk in Mediterranean fire-prone areas. In this study, the minimum travel time (MTT) fire-spread algorithm as implemented in FlamMap was applied to assess the potential of alternative fuel treatments for lowering wildfire losses in a 5,740-ha study area in eastern Sardinia, Italy. Twenty-seven wildfires at 10-m resolution were simulated considering three wind speeds (15, 18, and 21 km h^{-1}) to compare fuel treatments: no treatment (NT), irrigated agroforestry areas with shrub clearing (T1), prescribed fire in eucalyptus stands (T2), and irrigated grasslands (T3). The simulations replicated a recent large wildfire that occurred in the study area (Orrì wildfire, 2019) and considered the weather and fuel moisture conditions associated with this event. The average wildfire exposure outputs (burned area, probability of burning, conditional flame length, potential crown fire occurrence, and surfaces withflame lengths above 2.5 m) decreased after fuel treatments, compared to no treatment. T1 was the most effective strategy in mitigating wildfire hazards and provided the most significant performance for several wildfire exposure indicators. Treating only 0.5% of the study area (~ 30 ha) resulted in a decrease in all wildfire exposure metrics to ~ 10% within the study area. In addition, the total surface characterized by high flame length (average > 2.5 m) was the lowest in the T1 treatment. This study can help land and fire managers optimize fuel treatment opportunities and wildfire risk mitigation strategies in Mediterranean areas.

Keywords Fuel treatment strategies · Fire prevention · Mediterranean areas · Minimum travel time (MTT) · Wildfire exposure

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Introduction

Wildfires pose substantial threats to population structures and ecosystems of many Mediterranean areas due to the high heterogeneity of vegetation, topography, and climate conditions. In the Mediterranean basin, a relatively limited number of large wildfires is responsible for most losses and the area burned (Fernandez-Anez 2021). Climate and land-use changes can further increase the frequency of large fire events in future years (Castellnou et al. 2019; Gomes Da Costa et al. 2020). From this point of view, the largest wildfire of the last 30 years occurred recently in Sardinia (July 2021), with over 12,000 ha burned and causing substantial losses in forest ecosystems and farmlands. The expansion of rural–urban interfaces within the Euro-Mediterranean region will increase future challenges in wildfire risk management. Current fire management policies are almost entirely focused on suppression and do not adequately address the main driving factors of wildfires (Alcasena et al. 2019; Moreira et al. 2020). To mitigate wildfire effects, the implementation of cost-effective fuel treatments are widely recommended (Salis et al. 2016, 2018; Alcasena et al. 2017, 2019). Fuel treatments, including prescribed fire and mechanical thinning, can significantly reduce the impacts of wildfires by reducing surface and canopy fuel loadings (Calkin et al. 2011; Palaiologou et al. 2020). The impacts of fuel treatments may change broadly at the stand level depending on treatment type, size, and age (Beverly et al. 2020), as well as their spatial patterns and rate of implementation (Finney et al. 2007; Ager et al. 2010). These treatments are not only effective management tools for mitigating wildfire risk but also increase the opportunities for successful, safe, and risk-based wildfire suppression (Thompson et al. 2013; Calkin et al. 2014; Salis et al. 2021).

Simulation modelling has been used for evaluating wildfire exposure and wildfire risk-mitigation strategies from the forest stand scale to the landscape, regional, and national levels (Collins et al. 2011; Ager et al. 2020). Fire simulation models such as FlamMap (Finney 2006) are increasingly used in the European Union to assess wildfire hazard and risk (Xofis et al. 2020; Palaiologou et al. 2021; Salis et al. 2013), as well as the effects of fuel treatment on wildfire spread and behavior at a landscape scale (Cortes-Molino et al. 2020; Molina et al. 2021). FlamMap requires gridded geospatial input data on topography and fire behavior prediction (FBP) fuel types, along with weather streams. The application of FlamMap, which has already been calibrated and validated for Mediterranean areas (Mallinis et al. 2016; Alcasena et al. 2019) and elsewhere (Jahdi et al. 2020; Galizia et al. 2021; Oliveira et al. 2021), may help in quantifying and in better understanding the effects of different treatments, landscape features, and climates on wildfire risk reduction. As regards fuel reduction treatments, modelling studies predict greater wildfire losses in untreated scenarios than in treated ones (Ager et al. 2014, 2017; Marshall et al. 2020; Palaiologou et al. 2020). Recent studies have also demonstrated the effectiveness of various fuel treatments to limit wildfire exposure at landscape scales in fire-prone Mediterranean areas. Salis et al. (2016) evaluated various fuel treatments for reducing wildfire losses in Sardinia, Italy. The road protection alternative provided the highest performance in terms of wildfire exposure metrics. Alcasena et al. (2018) utilized spatial optimization to distribute and prioritize prescribed fires in northeastern Spain. The results revealed an optimization system for the design of strategically located treatment unit arrangements that effectively disrupted major fire growth and reduced potential losses in developed areas. Palaiologou et al. (2020) used simulations to create an optimized arrangement of fuel treatments in Greek forests. Fuel treatment effectiveness in their study was achieved with an optimized distribution of treatment units on an area of more than 200 ha. Benali et al. (2021) analyzed several fuel treatments effects on wildfire risk reduction in central Portugal. Increasingly, these studies have illustrated that the frequency of large wildfires can be reduced through the collective impact of numerous fuel treatments with specific designs and densities.

However, there is still a lack of operational studies documenting how fuel treatments may mitigate fire risk and quantify their effectiveness using fire behavior indicators in the Mediterranean areas. Additional research is needed to characterize the interactions between fuel treatments and wildfires to help bridge the primary knowledge gaps and provide technical guidance to inform future planning and research priorities. This study assesses the effects of fuel treatment alternatives at the landscape level and at the settlement level to decrease wildfire exposure. How treatment effectiveness is influenced by diverse wind speed conditions is also evaluated. Two main treatments were analyzed: ladder fuel removal and dead fuel loading reduction. These treatments were selected because they are commonly applied in Mediterranean areas but need to be tailored to specific landscapes. The spatially explicit fire behavior model FlamMap, based on the MTT (minimum travel time) algorithm (Finney 2006), was used to simulate pre-and post-treatment wildfire behavior in the landscape. The results of this study will support the planning and optimization of fuel management strategies that minimize wildfire risks in the Mediterranean basin.

Materials and methods

Study area

The study area covers 5,740 ha on the eastern coast of Sardinia, Italy. The area is situated near the municipality of Tortolì (N 39°55’, E9°39’; Fig. 1) and is characterized by several tourist values that cause an increase in population pressure, especially in summer. In 2019, the study area was affected by a large wildfire (Orrì, 13 July 2019) which

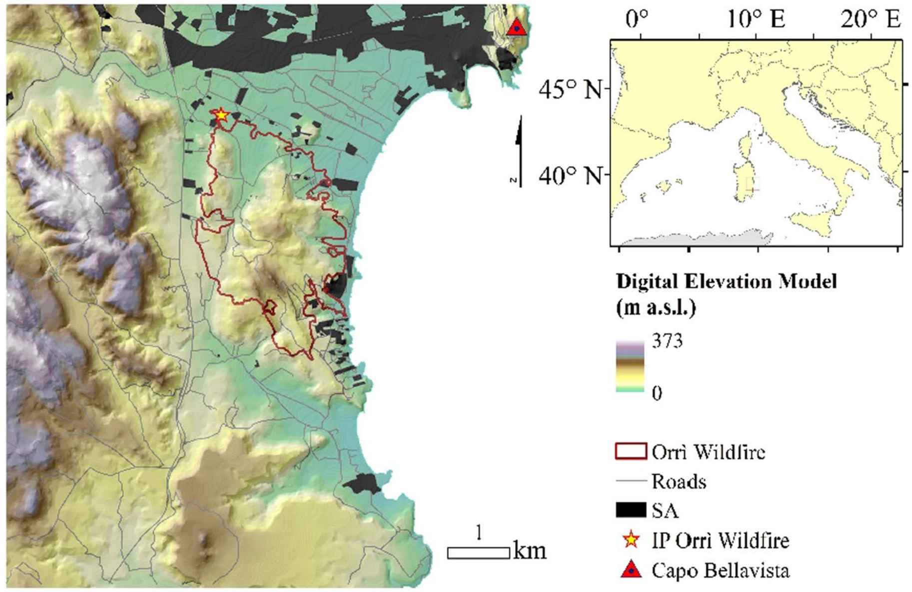

Fig. 1 Map of the study area along with the area burned (red polygon) by a large wildfire (Orrì, 13 July 2019), roads, settlement areas (SA), and digital elevation model (DEM)

threatened a tourist resort and nearby beaches.The topography is widely flat and hilly, and the average elevation is approximately 80 m a.s.l. while the highest peak is 374 m a.s.l. From a geo-pedological perspective, the area is mostly characterized by intrusive rocks (granites, granodiorites) that cover roughly 70%. Eolian sandstones and calcareous crusts cover 16%, and basalts cover 11% (Aru et al. 1991). The climate is typically Mediterranean with hot, dry summers and cold, wet winters. The average annual rainfall varies between 500 and 600 mm, with peak rainfalls at the highest elevations. The average annual temperature is 18 °C, and the maximum is often above 30 °C in summers (Chessa and Delitala 1977). The vegetation is largely herbaceous pastures, agricultural lands, and permanent crops in the flat areas. However, the most relevant natural vegetation in the hill areas is largely shrublands of *Olea europaea* L., *Pistacia lentiscus* L., *Phillyrea angustifolia* L., *Phillyrea latifolia* L., and *Cistus* spp. Near the beaches and in neighboring lands, plantations of eucalyptus globulus Labil. are present.

Wildfire data

According to the 2005 – 2019 fire database provided by the Sardinia Forest Service, the study area was affected by approximately 385 fires with a total area burned of about 1,130 ha. Overall, around 70% of the wildfires were below 0.1 ha and burned less than 1% of the total burned area. In contrast, less than 1% of the fires burned more than 100 ha and accounted for approximately 50% of the total area burned. Most wildfires were from July to September. Most of the area burned was related to the Orrì wildfire (Fig. 1), which ignited on July 13, 2019, and burned around 600 ha. The largest fire growth was observed in the first 5 to 6 hours. The day of the wildfire was characterized by strong, cold mistral winds with average speeds of 21 km h^{-1} and maximum gusts of around 75 km h^{-1} (Capo Bellavista weather station, https://it.tutiempo.net/[1]).

Input data for wildfire modelling

The data used for wildfire modelling are those required by FlamMap: gridded landscape files (topography and fuel characteristics) and weather conditions (wind speed and wind direction information and fuel moisture conditions). Topographic layers were derived from the 10-m digital elevation data of the Island (www.sardegnageoportale.it[2]), which was used to prepare the elevation, slope, and aspect rasters or spatial data models of the study area (Fig. 1). Spatial land use data were obtained through the analysis and combination of the 2008 Sardinia Land Use Map (www.sardegnageoportale.it), photointerpretation of aerial photos, and satellite images. Sardinia land use data were converted to 13 fuel types by grouping the original 71 land use classes into fuel models, as described in Table 1. The main characteristics of the fuel models are shown in Table 1 and Fig. 2. For canopy characteristics, reference values were based on the average characteristics of the canopy in the area.

Fuel moisture content (1-h and 10-h time lags) was estimated based on Pellizzaro et al. (2005, 2007) and Salis et al. (2015), which used sampling data obtained in Sardinia in previous years. These values are above the 97th percentile and reflect fuel moisture conditions frequently associated

[1] https://it.tutiempo.net/ [accessed on 14.04.2022].

[2] https://www.sardegnageoportale.it [accessed on 14.04.2022].

Table 1 Summary of fuel models parameters used as simulation inputs. FM 41, 42, and 43 are the fuel models used to characterize the fuels in the treated areas for the scenarios T1, T2, and T3, respectively

Fuel model code	Dead fuel load (t ha^{-1})	Live fuel load (t ha^{-1})	Fuel bed depth (cm)	Standard fuel model	Fuel moisture values					Canopy height (m)	Canopy base height (m)	Canopy bulk density (100 kg m^{-3})	Land use classes
					1 h	10 h	100 h	LiveH	LiveW				
FM 24	2	0	20	Mod 1 (Anderson 1982)	5	7	9	100	100	0	0	0	Grasslands
FM 25	4	0	30	Pers. comm	5	7	9	100	100	0	0	0	Herbaceous pastures
FM 26	2	0	15	Mod 1 (Anderson 1982)	5	7	9	100	100	4	1	16	Permanent crops
FM 27	5	4	60	Arca et al. 2009	5	7	9	100	40	5	0	16	Low mediterranean shrubs
FM 28	12	12	140	Arca et al. 2009	6	8	10	100	70	0	0	0	High mediterranean shrubs
FM 29	4	4	30	Pers. comm	5	7	9	100	70	8	2	16	Agroforestry areas
FM 30	4	1	30	Pers. comm	6	8	10	100	50	15	3	22	Eucalyptus stands
FM 31	12	2	30	TL4 (Scott and Burgan 2005)	6	8	10	100	70	10	2	16	Broadleaf forests
FM 32	5	2	15	TU1 (Scott and Burgan 2005)	6	8	10	100	70	12	7	14	Conifer forests
FM 33	2	12	200	Pers. comm	6	8	10	100	50	8	2	0	Riparian zones
FM 41	0.1	1.1	10	Pers. comm	9	10	11	100	100	8	2	16	Treatments in agroforestry areas
FM 42	0.2	0.2	10	Pers. comm	6	8	10	100	50	15	3	22	Treatments in eucalyptus stands
FM 43	0.1	1	10	Mod 1 (Anderson 1982)	8	9	10	100	100	0	0	0	Treatments in grasslands

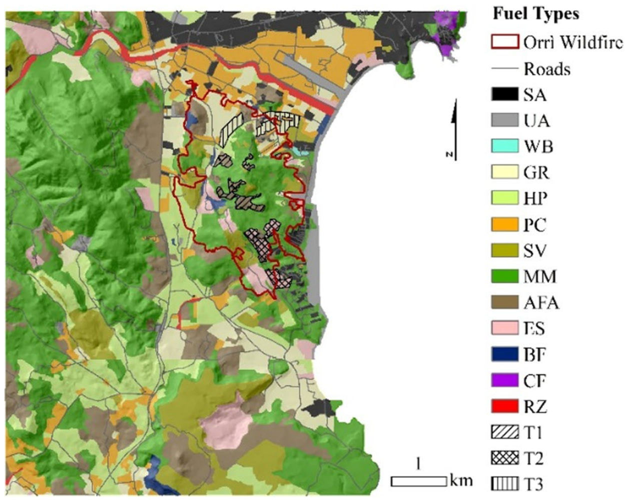

Fig. 2 Fuel types and locations for the three fuel treatment scenarios. SA = settlement areas; UA = unburnable areas; WB = water bodies; GR = grasslands; HP = herbaceous pastures; PC = permanent crops; SV = sparse vegetation; MM = Mediterranean maquis; AFA = agroforestry areas; ES = eucalyptus stands; BF = broadleaf forests; CF = conifer forests; RZ = riparian zone; T1 = summer irrigation and shrub removal in agroforestry areas; T2 = prescribed burning in eucalyptus stands; T3 = summer irrigation in grassland. The red polygon designates the Orrì wildfire

with large wildfires in the study area. Moisture values for different fuel models in the study area are shown in Table 1. Wind direction as an input was derived from the dominant winds observed during the Orrì wildfire (NW) and from weather data, wildfire reports, and personal communications with the Sardinia Forest Service.

Fuel treatment alternatives

We hypothesized three fuel treatments to modify dead and live fuel characteristics and lower wildfire spread and behavior at the landscape level (Table 2; Fig. 2 and Fig. S1). The treatments were simulated on a single unit of land characterized by specific fuel models (29, 30, and 24, see Table 1), and covered 0.5% of the study area. The treatments consisted of simple, low-cost fuel management operations (summer irrigation, removal of live shrub fuels, and prescribed burning) for agroforestry areas, eucalyptus stands, and private grasslands, and were defined based on interactions with the Sardinia Forest Service. Planned treatments in agroforestry areas were based on the combination of summer irrigation and shrub removal (T1); live shrub fuel was removed before irrigation in the T1 treatment. In addition, treatment based on prescribed burning as a means of reducing wildfire hazard (T2), converted the treated units into non-burnable areas in eucalyptus stands. Finally, the third fuel treatment (T3) was based on summer irrigation in grasslands.

Wildfire simulation modelling

Wildfire spread was simulated over the study area using the MTT fire spread algorithm (Finney 2002) in FlamMap (Finney (2006). FlamMap is based on Rothermel's (1972) surface fire spread model. Models such as Van Wagner's (1977) crown fire initiation model, Rothermel's (1991) crown fire spread model, Albini's (1979) spotting model, Finney's (1998) and Scott and Reinhardt's (2001) crown fire calculation method, and Nelson's (2000) dead fuel moisture model are also integrated into FlamMap. This was used to simulate wildfire for each fuel treatment. For each treatment, 27 events were simulated using as reference the ignition point of the Orrì wildfire, and wind speeds of 15 km h^{-1}, 18 km h^{-1}, and 21 km h^{-1}. In total, 108 simulations were analyzed. The burn period was set equal to six hours and produced fire sizes that approximated the wildfire perimeter observed during the event of 13 July 2019. Simulations were conducted at 10-m resolution, consistent with the input data. For spot fires, previous studies found that spotting probabilities in the range of 1% – 2% were usually a good compromise to accurately predict large wildfires (Alcasena et al. 2015). Therefore, spot fire probability was set to 2%, consistent with active fire spread observed during the large wildfires in the study area. Fire suppression was not simulated.

The input variables, along with the model settings. were used to perform deterministic simulations for the case study. Analysis focused on the following outputs: burned area (BA), probability of burning (PB), conditional flame length (CFL), and potential crown fire occurrence (PCF). PB is the probability that a wildfire will impact a point on the landscape during a given time and is the result of complex interactions of topography, fuels, weather, and ignitions (Parisien et al. 2005; Miller and Ager 2013). In addition, a probability weighted CFL is a measure of wildfire hazard (Thompson et al. 2011; Ager et al. 2017). Fires of increasing CFL would be increasingly damaging to vital assets and infrastructures and are challenging some of the wildland firefighting programs. In this study, CFL > 2.5 m was identified as a threshold for controlling wildfires in areas where fire intensity can potentially overwhelm fire suppression capabilities (Alcasena et al. 2018; Salis et al. 2021). Finally, the PCF was identified for a given pixel and fuel model when the flame length value was higher than the canopy base height (Salis et al. 2016).

The wildfire exposure to human settlements was calculated using the 10-m CFL grid and the number and the percentage of buildings were calculated with values > 2.5 m. The Open Street Map (OSM) of buildings shapefiles (https://www.geofabrik.de/[3]) was used, which provided accurate locations of all buildings with a resolution from 30 to 60 cm. Structure centroids were calculated and CFL values were

[3] https://www.geofabrik.de/ [accessed on 14.04.2022].

Table 2 Description of the different fuel treatment scenarios

Main information	Fuel treatments		
	T1	**T2**	**T3**
Area treated (ha)	29.3	29.7	31.2
Fuel treatment type	Summer irrigation in agroforestry areas	Prescribed burning in Eucalyptus stands	Summer irrigation in grasslands
Treatment constraints	Irrigated land under tree cover to reduce 1-h dead fuel load and increase herbaceous live fuel load; low shrubs were removed before irrigation	Prescribed fire in eucalyptus stands to reduce 1-h dead fuel load and shrub live fuel	Irrigated land to create a non-burnable area near tourist areas

Table 3 Average values of burned area (BA, ha), probability of burning (PB, %), conditional flame length (CFL, m), and potential crown fire occurrence (PCF, ha) for NT (no treatment) and the three fuel treatments T1, T2, T3. Standard deviation values are under parenthesis

Fuel treatments	BA, ha	PB, %	CFL, m	PCF, ha
NT	704.2 (193.5)	69.2 (34.5)	2.7 (2.0)	564.9 (155.2)
T1	661.5 (193.1)	65.9 (36.2)	2.5 (2.0)	512.0 (150.4)
T2	695.4 (192.8)	68.9 (34.8)	2.6 (2.1)	558.3 (155.6)
T3	690.1 (203.4)	66.1 (35.7)	2.7 (2.1)	539.6 (160.5)

assigned to each building, identifying instances where the CFL was > 2.5 m.

The Kruskal–Wallis non-parametric test evaluated the significance of differences affecting the variables (BA, PB, CFL, and PCF) for the different treatments and levels of wind speed. The Bonferroni *post-hoc* test was used for pairwise comparison among the treatments to assess the group levels. To evaluate the effects of the treatments on landscape areas with high values of CFL (> 2.5 m), the Kappa statistic, derived from the confusion matrix between the raster files provided by the simulator for each treatment and wind scenario, was calculated. The Kappa statistic measures the level of agreement among the treatments and wind scenarios for the landscape areas with CFL > 2.5 m. The significance of the association was evaluated by the McNemar's $\chi 2$ test.

Results and discussion

Effect of fuel treatments on wildfire exposure at the landscape scale

All fuel treatments consistently reduced wildfire exposure; this effect was unequivocal for all scenarios tested (Table 3). The most effective fuel treatment (T1) resulted in higher BA, PB, CFL, and PCF reductions compared to NT (Table 3). However, in some cases, PB and CFL values of the T2 treatment were not significantly different from those of the NT. These results also appear to be consistent with previous studies in Sardinia (Salis et al. 2016, 2018).

Simulated fuel treatment T1 reduced the mean BA from 704 to 661 ha (7%), whereas T2 and T3 reduced BA by less than 2% (Table 3). The values obtained in our study for BA are like those reported by Ager et al. (2010), where an average reduction of 7% – 8% wildfire size was reported. Similarly, T1 and T3 differed from the NT conditions in PB reduction from 69 to 66% (Table 3). Our results confirm the assumptions of the Sardinia Forest Service which considered T1 (irrigated agroforestry with shrub clearings) to be the best treatment due to its position considering the topography. Irrigated areas in the T1 scenario are known as the defensible zones for firefighting forces in a wildfire (Fu et al. 2021). However, in recent years grassland irrigation has gained relevance in the South European/Mediterranean region due to the increased frequency of drought (Peratoner et al. 2017). Since irrigation water demand is significant, especially for agriculture, using irrigation for wildfire preventive purposes can be limiting.

The treatments had no significant effects on the canopy base height of the fuel stratum, and the type of treatments hypothesized and the reduction of CFL and PCF caused by the different treatments were small (Table 3). This pattern has been replicated in other studies (Cruz et al. 2014; Salis et al. 2018). In this study, the average CFL of 2.7 m in the NT scenario decreased by a maximum of 6% for T1, T2, and T3 treatments (Table 3). The average PCF of the NT condition was 565 ha, while fuel treatments T1, T2, and T3 yielded average PCFs of 512, 558, and 540 ha, respectively (Table 3). Fuel treatments may become more effective as the extent of the area being treated increases, which has been validated by other studies in the Mediterranean (Salis et al. 2016, 2018). For this reason, our work showed limited differences between treatment strategies and no treatment, considering the amount of the area treated was only 0.5% of the total study area. Furthermore, the amount of area treated will become more important as the number of wildfires increases (Loudermilk et al. 2014). A balance may be reached in the use of fuel treatments for reducing wildfire risk if the costs of treatments do not exceed the benefits obtained by reducing the burned area (Mercer et al. 2008; Thompson et al. 2013).

Table 4 illustrates BA, PB, CFL, and PCF for six hours of simulation, accounting for all simulations (treatments and wind speeds). For the NT scenario, the simulated BA under the three different wind speeds ranged between 509 ha (WS15) and 870 ha (WS21). In addition, Fig. 3 depicts the results of PB, CFL, and PCF for the NT scenario considering different wind speeds (15, 18, and 21 km h^{-1}). As expected, the proportion of the landscape that burns increases with wind speed (Table 4 and Fig. 4a). Moritz et al. (2010) and Salis et al. (2018) reported similar effects promoted by wind speed. At the highest wind speed (WS21), the burned area in agroforestry areas (T1) was reduced by about 5%, while for the prescribed fires in the eucalyptus stands (T2) and for irrigated grasslands (T3) it was less than 1%. At the lowest wind speed (WS15), T1, T2, and T3 reduced the average burned areas, relative to the no treatment condition, by 7%, 2%, and 5%, respectively (Table 4). These are different from the results of Salis et al. (2018), in which an increase in the effectiveness of the fuel treatment due to stronger wind conditions was obtained. With regards to the area burned, Kruskal–Wallis analysis showed that all treatments were significantly different (Table 4).Fig. 5 shows the effects of different fuel treatments (T1, T2, and T3) on the probability of burning (PB) based on wind speed. T1 was the most effective treatment in reducing PB, although differences with the other treatments were insignificant (Figs. 5a, b, c). The results indicate a slight reduction in PB under T2, with no significant difference compared to NT, for wind speeds WS15 and WS21 (Table 4 and Fig. 4b). Moreover, the magnitude of the reduction was limited to 3.2% by 0.5% of the study area treated. This result agrees with similar work by Thompson et al. (2017), where the average wildfire reduction was 3.7% for 0.7% of the landscape that was treated. Note that the reduction in PB is negative, and some pixels experienced a slight increase (Figs. 5a–i). This increase in PB and other features in the treated landscape is reported in other simulation studies (Oliveira et al. 2016; Palaiologou et al. 2018; Salis et al. 2018). Most of the observed increase can be due to either stochastic spots within the model or treatments changing wildfire behavior (rate of spread and fire spread pathways) (Thompson et al. 2017). Furthermore, fuel treatments at the landscape scale may create unintended negative externalities, as they reduce the burn severity of the treated area but may increase severity in adjacent, untreated areas (Calkin et al. 2014). From this perspective, values at risk in the adjacent areas should be examined before implementing treatment, taking weather conditions and fire spread probabilities into account.

Table 4 Average values of burned area (BA, ha), probability of burning (PB, %), conditional flame length (CFL, m), and potential crown fire occurrence (PCF, ha) for NT (no treatment) and the three fuel treatments (T1, T2, T3), considering the three wind-speed conditions (15, 18, 21 km h^{-1}). Standard deviation values are under parenthesis

Fuel treatment scenarios	BA, ha			PB, %			CFL, m			PCF, ha		
	15	18	21	15	18	21	15	18	21	15	18	21
NT	509.3^{a} (112.4)	733.8^{a} (122.0)	869.5^{a} (140.4)	67.4^{a} (35.4)	70.7^{a} (36.2)	73.8a (34.4)	2.6^{a} (1.9)	2.7^{ab} (2.0)	2.8^{a} (2.1)	412.3^{a} (98.0)	589.7^{a} (99.6)	692.7^{a} (155.2)
T1	471.2^{b} (102.3)	682.1^{b} (123.2)	831.4^{b} (147.6)	65.9^{b} (36.8)	66.3^{b} (38.4)	69.5b (36.4)	2.4^{b} (1.9)	2.5^{c} (1.98)	2.6^{b} (2.1)	367.2^{b} (86.4)	530.1^{b} (98.9)	638.7^{b} (150.4)
T2	500.3^{c} (114.2)	724.2^{c} (115.5)	861.9^{c} (139.6)	67.2^{a} (35.3)	72.1^{c} (35.6)	73.5a (34.8)	2.6^{a} (1.9)	2.7^{a} (2.0)	2.8^{a} (2.1)	404.4^{c} (100.2)	583.2^{c} (96.2)	687.4^{c} (155.6)
T3	483.9^{d} (114.5)	717.7^{d} (131.6)	868.7^{d} (139.2)	64.6^{c} (36.4)	67.7^{d} (37.2)	71.5c (35.7)	2.6^{c} (1.9)	2.6^{b} (2.0)	2.8^{a} (2.1)	381.6^{d} (100.9)	565.4^{d} (106.3)	671.9^{d} (160.5)

Different letters in the same column indicate significant differences at $P < 0.05$

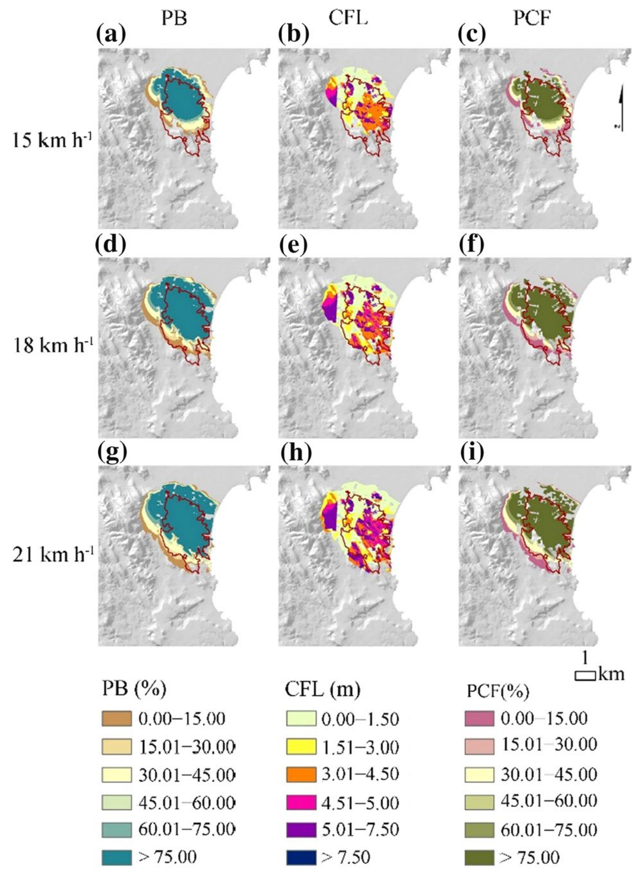

Fig. 3 Maps of probability of burning (PB (%), a, d, g), conditional flame length (CFL (m), b, e, h), and potential crown fire occurrence (PCF (%), c, f, i) for no treatment (NT) at different wind speeds (15, 18, and 21 km h^{-1}); the red polygon designates the Orrì wildfire

Figures 6 a-i show the difference in conditional flame length (CFL) under different treatments (T1, T2, and T3) and wind speeds (15, 18, and 21 km h^{-1}). The reduction of the mean CFL had no significant effects on the landscape in the case of the T2 and T3 treatments; slight differences were found among the three wind speeds (Table 4 and Fig. 4c). The highest wind speed (WS21) had the highest mean CFL (2.8 m) (Table 4 and Fig. 4c). Regardless of wind speed, average CFL values for the T1 treatment were statistically lower compared to NT, while T2 and T3 treatments were not statistically different from the NT (Table 4). These results confirmed the effectiveness of T1, irrigated agroforestry areas with shrub clearing. However, as noted above, the typology and size of treatments did not allow for large reductions in CFL.

Figure 7 shows the total surfaces affected by conditional flame lengths > 2.5 m for each wind speed and the different treatments. The 2.5 m CFL threshold allowed for the identification of the most dangerous areas for ground-based fire suppression for each fuel treatment (Andrews 2011; Alcasena et al. 2015; Salis et al. 2021). All fuel treatments effectively reduced the average CFL as well as the area of high fire intensity. This decrease followed a pattern similar to Fig. 6a-i but showed higher percentage reductions. Areas with CFL > 2.5 m had large decreases with T1 (approximately 9%), while the corresponding reductions with T2 and T3 were less significant (< 2%). Reduction in fuel load and height due to removal of shrubs in T1 decreased CFL as a function of fire intensity. This result is similar to the findings of Marino et al. (2014) in the Mediterranean areas. For the untreated condition, 348 ha presented CFL > 2.5 m at the lowest wind speed (15 km h^{-1}). The area with CFL > 2.5 m increased to 480 ha and 589 ha at wind speeds of 18 km h^{-1} and 21 km h^{-1}, respectively. In T1 treatment, higher reductions compared to the NT of 14% (300 ha) were observed at the lowest wind speeds. However, the reduction was much lower for treatments T2 and T3 than for the T1 treatment, which resulted in inefficient suppression capabilities due to high fire intensity. To compare the surfaces affected by CFL > 2.5 m, the Kappa statistic was calculated (Table 5). Although all the comparisons shown provide significant values of the McNemar's $\chi 2$ test for $P > 0.01$, the Kappa values indicate that T1 is characterized by lower values of association with NT and T3 treatments for each wind speed, and lower values of association with T2 for 15 km h^{-1}, confirm in Fig. 7. Based on the results T1 (irrigated agroforestry with shrub clearing) was strategically located with respect to fuel types and topography, in which the slope aspect changes in the treated area. Based on the potential crown fire (PCF) results shown in Table 4, T1 was the most effective, reducing PCF across the study area (roughly 10%). In both T2 and T3, the PCF differences were more limited but significant for all wind conditions (Table 4 and Fig. 4d). The changes in PCF, as quantified by the wind speed required for the occurrence of crown fires, were not readily obvious (i.e., in scenarios T2 and T3). For PCF, WS21 had the largest range of values with the highest mean value (672 ha). T1 reduced the PCF by 10% (Table 4). In fact, the more open conditions of the landscape resulting from fuel treatment T1 (shrub clearing along with irrigation) allowed wind conditions to impact flame lengths and crown fire activity more drastically compared to the untreated area, as described by Fitch et al. (2018). On the other hand, fuel reduction (by prescribed fire) in eucalyptus stands (T2) has seemingly little effect. Fuel treatment in eucalyptus stands is a matter of controlling the surface fuel build-up because the trees are established at their final spacing and quickly grow in height (Mirra et al. 2017). However, prescribed fires have been prevented with decorticating bark grown in short-rotation forest systems, but they reduce surface fuel loads more effectively than other treatments in eucalyptus stands (Fernandes et al. 2011; Pinto et al. 2014). In addition, prescribed fires are generally a cost-effective way of reducing live understory and fine dead fuel loads (Cochrane et al. 2012). However, as a standalone practice in some landscapes, prescribed burning may not have a role in wildfire management and may appear

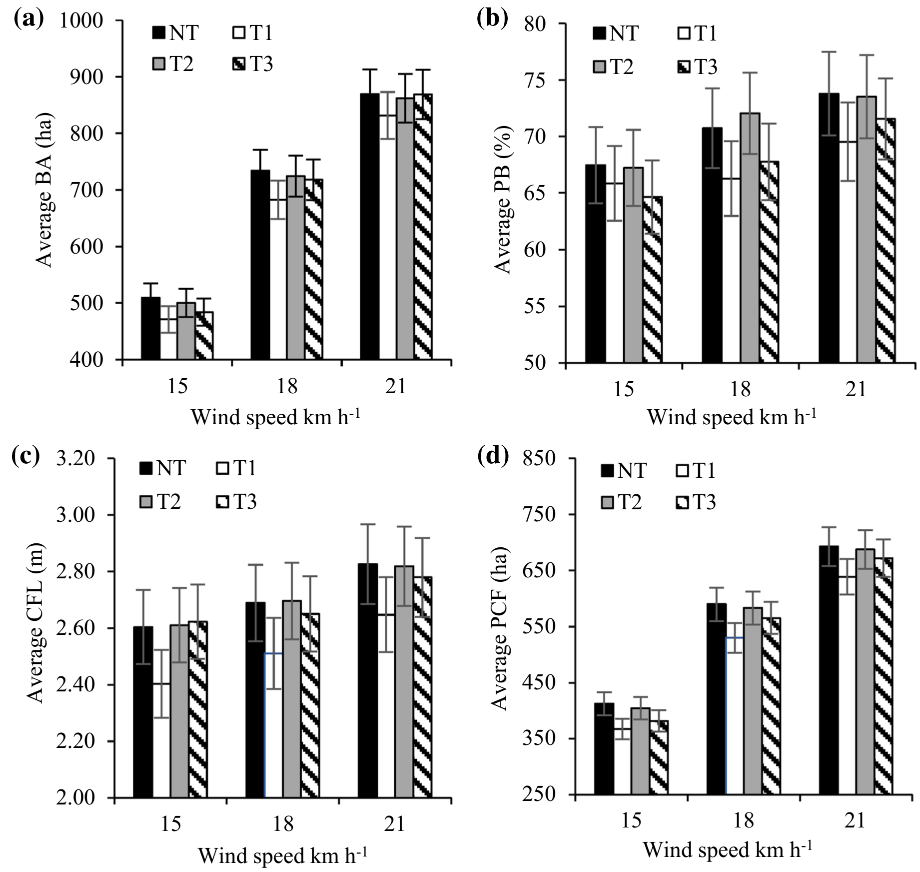

Fig. 4 Effects of the fuel treatments T1, T2, and T3 and wind speed conditions on average burned area (BA (ha)), **a**; probability of burning (PB (%)), **b**; conditional flame length (CFL (m)), **c**; potential crown fire occurrence (PCF (ha)), **d**. The error bars represent standard deviation values

to be ineffective or even detrimental as a treatment for reducing vegetation in subsequent wildfires. When combined with mechanical fuel reductions (thinning), prescribed burning is effective in reducing future fire severity (Cochrane et al. 2012). Nevertheless, prescribed fires have been used to control fire regimes and reduce wildfire risk in Mediterranean areas (Fernandes et al. 2013). Our findings and previous studies indicate that it is necessary to scale up prescribed burning to effectively lower wildfire risk (Vaillant et al. 2009; Alcasena et al. 2018; Davim et al. 2021).

Effect of fuel treatments on wildfire exposure on settlements

More than 17% of human settlements (> 4 ha) overlapped with the Orrì wildfire (Fig. 1). Reducing the number of specific structures exposed to destructive wildfires is another important benefit of implementing the treatments (Schmidt et al. 2008; Safford et al. 2009; Ager et al. 2010). The FlamMap fire behavior simulator was used to compare fuel treatments that met the objective of reducing wildfire risk to human settlements. The location of fuel treatments and their effect on wildfires to population structures in the Mediterranean area was also shown by Salis et al. (2016) and Alcasena et al. (2022) using a fire spread modelling approach and our study showed similar results. Overall, the treatments increased the protection of valued resources (residential houses) compared to no treatment (Fig. 8). Given the probability of having conditional flame length values > 2.5 m, on average, 61 residential houses presented values different from zero and could be therefore affected at high intensity. Human settlements included buildings located in areas with an 18%–38% probability of having conditional flame lengths > 2.5 m (Fig. 8). For the NT, the number of residential houses exposed was 64 and reduced to 57, 63, and 62 in scenarios T1, T2, and T3, respectively. As expected, T1 was the most effective in decreasing the number of residential houses exposed to wildfires. Again, the number of residential houses exposed to high flame length values increased with increasing wind speed (Fig. 8). The spatial arrangement associated with T1 achieved the most significant reductions in the number of residential houses exposed to all wind speeds among the treatments tested. For instance, in the highest wind speed (WS21), T1 gave an 8% reduction in the number of residential houses exposed compared to the NT. In the lowest wind speed, T1 decreased the number by approximately 13% compared to NT. In this treatment, fuel reduction outside and adjacent to the houses might reduce the potential flame and fire exposure (Calkin et al. 2014) and increase the effectiveness of wildfire suppression efforts,

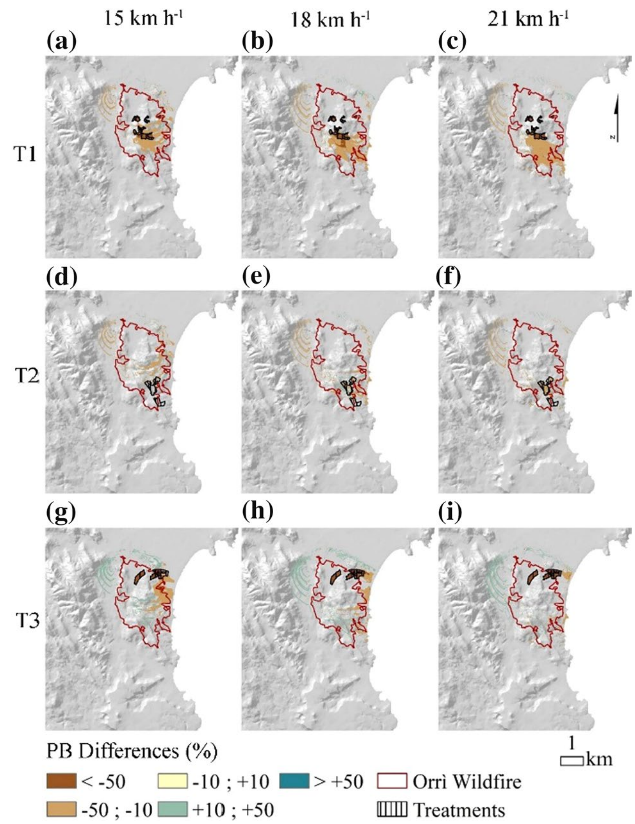

Fig. 5 Percentage difference in probability of burning (PB) between treated (T1, T2, and T3) and untreated scenarios and for different wind speeds (15, 18, and 21 km h^{-1}). Positive values indicate an increase in PB, while negative values indicate a reduction. Black polygons represent the treatments; the red polygon designates the Orrì wildfire

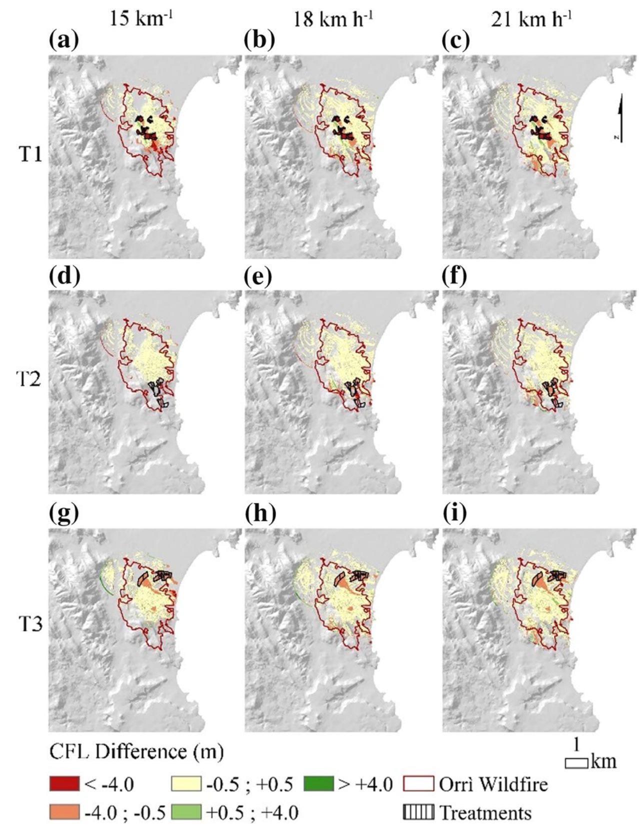

Fig. 6 Differences in conditional flame length (CFL, m) between treated (T1, T2, and T3) and untreated scenarios, and for different wind speeds (15, 18, 21 km h.$^{-1}$). Positive values indicate an increase in CFL, while negative ones a reduction. Black polygons represent the treatments, and the red polygon the Orrì wildfire

leading to reduced resource and property damages (Rideout et al. 2008).

Conclusions

This research presents a methodology based on the MTT (minimum travel time) fire spread algorithm to evaluate the effects of three fuel treatments on exposure to wildfire at landscape and settlement levels, considering three wind speeds. It can be concluded that all fuel treatments effectively reduced wildfire exposure and should be part of integrated fire management plans. Furthermore, different fuel management strategies demonstrably varied in their effectiveness. Irrigated agroforestry areas with shrub removal constituted the most efficient strategy for reducing wildfire exposure at landscape and settlement scales. It was presumed that this was due to effectively reducing surface and ladder fuels and the strategic location of treatments, emphasizing the need to find innovative ways to treat larger areas. Overall, wildfire exposure

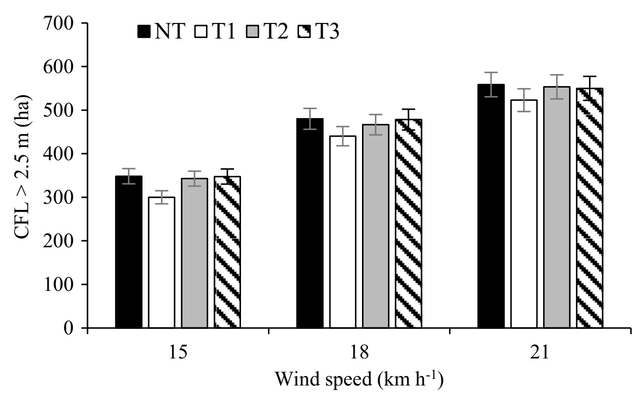

Fig. 7 Effects of fuel treatments (NT, T1, T2, T3) and wind speeds on the number of hectares with CFL > 2.5 m. The error bars represent standard deviation values

decreased 10% on average in the landscape (by less than 1% of the study area treated). Quantifying the complexity of wildfire and fuel treatment interactions provides land managers and policymakers with the means to track their

Table 5 Kappa statistic values of the different comparisons of treatments and wind speeds for areas with CFL > 2.5 m

Fuel treatments	15	18	21
NT—T1	0.90	0.93	0.94
NT—T2	0.98	0.96	0.98
NT—T3	0.95	0.96	0.96
T1—T2	0.91	0.94	0.95
T1—T3	0.86	0.91	0.92
T2—T3	0.95	0.95	0.96

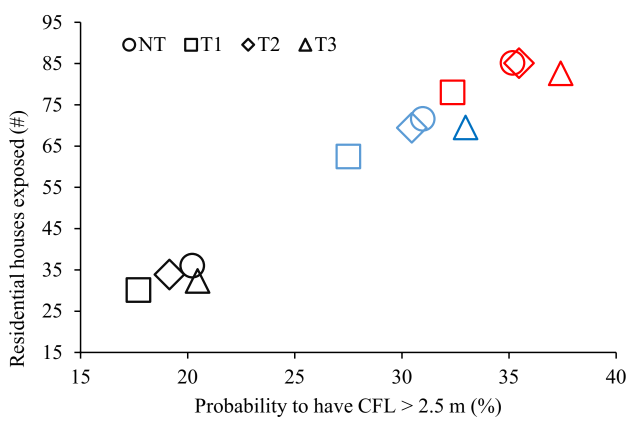

Fig. 8 Effects of fuel treatments (NT, T1, T2, T3) and wind speeds (black, blue, and red refer to 15, 18, and 21 km h^{-1}, respectively) on the number of residential houses exposed with conditional flame lengths > 2.5 m

potential to reduce wildfire losses. Nevertheless, future research should be oriented to testing the impacts of different fuel treatments on wildfires and comparing the results to determine the treatment to best achieve the desired results in wildfire behavior. It would provide better and more specific information about implementing a landscape fuel treatment, especially for Mediterranean ecosystems. Substantial investments in fuel management, especially in fire-prone Mediterranean ecosystems, are crucial for mitigating the potential impacts of climate change and agricultural land abandonment on fuel complexes and wildland fires. This research approach can help identify and plan the most effective strategies and spatial locations of fuel treatments in agropastoral areas with limited portions of land to be treated, especially for Mediterranean ecosystems.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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