Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area

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2 Mediterranean area

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18 Abstract

19 The goal of this work is to evaluate by a modeling approach the effectiveness of alternative 20 fuel treatment strategies to reduce potential losses from wildfires in Mediterranean areas. We 21 compared strategic fuel treatments located near specific human values versus random 22 locations, and treated 3, 9 and 15% of a 68,000 ha study area located in Sardinia, Italy. The 23 effectiveness of each fuel treatment was assessed by simulating 25,000 wildfires using the MTT fire spread algorithm. The simulations replicated severe wildfires observed around the 24 study area, using historic weather and fuel moisture conditions (97th percentile). Wildfire 25 26 exposure profiles for the study area as a whole and for locations with specific values of interest were analyzed. Results indicated significant variations in wildfire exposure among 27 28 and within the fuel management strategies and treatment intensities. The simulated mitigation 29 strategies substantially decreased the average wildfire exposure with respect to the untreated 30 condition, and this effect was unequivocal for all strategies. Increasing the percentage of land 31 treated improved the effectiveness of all fuel treatment strategies. The strategy based on road 32 protection provided the highest performances for several wildfire exposure indicators. The 33 methodology presented in this work can be applied to facilitate the design of fuel 34 management programs and support policy decisions to address growing wildfire risk in the 35 region. This work is one of the first applications of fire simulation modeling to evaluate fuel management effectiveness on wildfire risk mitigation in the Mediterranean areas. 36

37 Keywords

Fuel treatment strategies; burn probability; MTT algorithm; Mediterranean Basin; wildfire
exposure; wildfire risk mitigation

40 Introduction

Wildfires represent a substantial threat to Southern European forests and ecosystems and every year cause extensive losses to anthropic infrastructures and values (Bassi *et al.* 2008; San-Miguel-Ayanz *et al.* 2013; Schmuck *et al.* 2014). Although the economic investments in fire suppression and fire crews training and preparation have progressively increased during the last decades, large wildfires still overwhelm suppression capabilities, spread for large distances and burn thousands of hectares (Costa Alcubierre *et al.* 2011; Alcasena *et al.* 2015*b*). Wildfire spread during these events represents the primary contributor to wildfire
losses and area burned (Ganteaume and Jappiot 2013; Salis *et al.* 2013). Mega-fires usually
occur under extreme weather conditions, such as strong winds, low relative humidity and
prolonged drought (Trigo *et al.* 2006; Viegas *et al.* 2009; Koutsias *et al.* 2012; Pausas and
Fernandez-Munoz 2012; Cardil *et al.* 2013, 2014; Salis *et al.* 2014).

Humans play a key role on influencing fire regimes, by means of anthropic fire ignitions, 52 implementation of socio-economic policies and land uses, and fire suppression activities 53 54 (Moreira et al. 2011). In the Mediterranean Basin, more than 90% of fire ignitions are human-caused and follow complex spatio-temporal patterns related to anthropic and 55 56 biophysical variables (Koutsias et al. 2010; Lovreglio et al. 2012; Oliveira et al. 2012; 57 Meddour-Sahar et al. 2013; Ager et al. 2014a; Salis et al. 2015). In recent years, the increase 58 and densification of anthropic activities and population in main towns, as well as in coastal 59 zones, has contributed to an increase in fire ignition sources in such areas (Martínez et al. 60 2009; Chas-Amil et al. 2013). Moreover, rural exodus and land abandonment during the last 61 decades prompted a rapid natural succession of vegetation in areas previously exploited for 62 livestock and agro-forestry activities. These changes in land use brought about a large expansion in shrubby, thicket fuels on previously marginal and rural lands, as well as the 63 development of understory vegetation and ladder fuels in previous timber production areas 64 65 (Pausas 2004; Bonet and Pausas 2007; Ruiz-Mirazo et al. 2012). The result was a transition from mosaic-managed type landscapes to a high fuel load, continuous and highly hazardous 66 67 vegetation complexes (Mazzoleni et al. 2004; Palahi et al. 2008; Fernandes et al. 2014). 68 Furthermore, fire exclusion policies have also played a role on fuel load accumulation and the growing incidence of intense and large wildfires (Badia et al. 2002; Pinol et al. 2005; 69 70 Xanthopoulos et al. 2006; Curt et al. 2013). Moreover, a substantial increase in fire 71 suppression costs in the last decade has limited investments in fuel management and fire

72 prevention (Calkin et al. 2005; Stephens and Ruth 2005; Prestemon et al. 2008; Hand et al. 73 2014). For these reasons, fire managers and policy makers need to adopt the best compromise 74 between fire control and fuel management approaches for the future, while considering that 75 the complete exclusion of wildfires is not a feasible and reasonable strategy in the long term 76 (Keane et al. 2008; Moritz et al. 2014). In the Mediterranean Basin, fire restoration and 77 management are a challenging proposition since many houses and values intermingle with wilderness and unmanaged lands, and thus managing wildfires for fuel management poses 78 79 unacceptable risks (Lampin-Maillet et al. 2010; Pellizzaro et al. 2012; Moritz et al. 2014). Fuel management strategies employ a combination of surface fuel loading, depth and 80 81 continuity reduction treatments (e.g., prescribed burns and mastication), silvicultural 82 practices to change tree crown structure (e.g., thinning and low-pruning), and the creation of 83 infrastructures and safety areas to facilitate fire suppression activities (e.g., road networks and 84 water points) (e.g.: Bovio 2002; Leone and Signorile 1997; Fernandes and Botelho 2003; 85 Xanthopoulos et al. 2006; Molina et al. 2011; Bovio and Ascoli 2013; Zagas et al. 2013; 86 Corona et al. 2015). Risk mitigation is strongly linked to landscape fuel management and 87 may involve a range of primary targets, strategies and spatial patterns depending on fire 88 management and protection objectives, land use laws, social and physical constraints, and budget (Parisien et al. 2007; Reinhardt et al. 2008; Ager et al. 2013; Hand et al. 2014; 89 90 Corona et al. 2015; Valor et al. 2015). Designing feasible strategies is a complicated problem 91 and a number of recent studies have explored appropriate spatial and temporal strategies and 92 the effects of various constraints on their performance in reducing wildfire exposure and risk 93 (Finney 2001; Agee 2002; Duguy et al. 2007; Finney et al. 2007; Wei et al. 2008; Ager et al. 94 2010; Elia et al. 2014; Chung 2015; Vogler et al. 2015). Most studies examining fuel 95 management strategies have applied probabilistic approaches based on fire spread simulators, and quantified the capabilities of fuel treatments in reducing losses from fires for specific 96

targets as measured by burn probability and flame length. Such approach has been
successfully implemented in many areas of the US and Canada (e.g.: Finney 2001, 2006;
Finney *et al.* 2007; Ager *et al.* 2007, 2010, 2013; Miller *et al.* 2008; Moghaddas *et al.* 2010;
Liu *et al.* 2013; Scott *et al.* 2013), while for the Mediterranean Basin this methodology is still
unexplored.

102 In Sardinia, new regional programs for rural development and fire management planning 103 emphasize the crucial role of fire prevention by fuel and land management to reduce losses 104 from wildfires under both current conditions and those expected in the future under climate 105 change (Sardinia Regional Government 2014a, 2014b, 2014c). As part of a larger effort to 106 develop scientific basis for landscape fuel treatment programs in fire-prone Mediterranean 107 ecosystems and in order to evaluate the effectiveness of competing fuel treatment strategies 108 in reducing losses from wildfires, we applied wildfire simulation and geospatial modeling 109 approach to test alternative strategies on a 68,000 ha study area located in North-east 110 Sardinia, Italy. We defined three fuel treatment strategies and objectives, and simulated fuel-111 type-specific modifications in load and height for measured portions of the landscape. We 112 then analyzed how these different strategies affected burn probability, wildfire intensity and 113 size, and other aspects of wildfire exposure. The work is the first application of spatially 114 explicit fire spread and behavior modeling in Sardinia, and one of the first in the 115 Mediterranean area, to evaluate the potential effects of competing fuel treatment strategies on 116 wildfire exposure and risk.

117 Material and Methods

118 <u>Study area</u>

The study area is located in Northeastern Sardinia, Italy, and has nearly 68,000 ha of land(Fig. 1). About 20% of the study area is classified as European Site of Community

Importance (EU 92/43/EEC Directive). The territory is mainly characterized by the granitic mountain complex of Monte Limbara, with orientation SW-NE, and by the Coghinas lake, the largest one of North Sardinia. The elevation of the study area ranges from about 45 m a.s.l. to the highest point of Punta Balistreri (about 1,350 m a.s.l.). Overall, the area is characterized by a complex topography, and about 25% of the land is above 600 m a.s.l. (Fig. 1).

The climate is Mediterranean, with hot and dry summers and cold and wet winters, and 127 128 intermediate conditions in spring and autumn. The average annual precipitation is about 650 129 mm in the plains, but peaks of more than 1,000 mm are common at the highest elevations. In 130 July, the average maximum and minimum temperatures range from 28.5 °C and 17.4 °C, 131 while in January from 9.2 °C to 3.8 °C, with some relevant gradients moving from the plains 132 of to the top the mountains (Chessa and Delitala 1997: 133 http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp). Following the Pavari 134 phytoclimatic classification (Arrigoni 1968), the study area is mostly represented by 135 Lauretum cold areas, and by Castanetum warm zones in north facing slopes and at elevation 136 above 1,000 m a.s.l..

137 The natural vegetation is mostly characterized by Quercus ilex and Quercus suber L. woods, 138 as well as high and dense Mediterranean maquis. In the hilly and mountainous areas of Monte 139 Limbara, the most representative shrub types are Erica arborea L. and Arbutus unedo L., 140 while Cistus monspeliensis L. and low shrubs cover the south facing slopes and the most degraded areas. The conifer woods occupy limited areas, and are mainly represented by 141 artificial plantations of Pinus pinea L., Pinus pinaster Aiton, and Pinus nigra ssp. laricio 142 143 Poir. On the whole, shrublands and forests occupy about 46,000 ha of the study area, which 144 corresponds to about 69% of the territory (Fig. 2). Anthropic areas cover approximately 850

ha of land, being the town and the industrial area of Tempio Pausania the most relevant anthropic zone of the study site. Fruit-bearing areas are mostly represented by sparse and family-farm vineyards and olive groves and cover about 2,300 ha of land; these land types are largely concentrated in flat areas and nearby the town of Tempio Pausania. Grasslands and agricultural areas are mainly devoted to herbaceous and horticultural productions and characterize about 20% of the study area, particularly in the plains (Fig. 2).

151 Wildfire data

152 To characterize wildfire history in the study area, we used the 1980-2010 fire database provided by the Sardinia Forest Service. This database collects information on ignition points 153 154 coordinates, municipality and date of ignition, and estimated fire size. Overall, from 1980 to 155 2010, the study area experienced about 800 fire ignitions; fire occurrence was almost totally concentrated in four months, from June to September, and about 60% of the events happened 156 157 from mid-July to late August. About 95% of the fires were smaller than 10 ha, while only 158 4.5% of ignitions were responsible for 90% of the total area burned in the study period (Fig. 159 3). The main fire causes in the study area are related to arson and negligence, while lightning 160 fires do not exceed 3% of the events. For this reason, roads and surroundings of villages, as 161 well as power lines, are common areas of fire ignitions.

To examine the weather conditions of the days with fire occurrence in the study area, we gathered daily meteorological data from the weather stations of Olbia and Alghero (North Sardinia) and from the reports of the Sardinia Forest Service (Sardinia Forest Service, personal communication 2014; www.tutiempo.es; www.centrometeo.com; www.wunderground.com).

167 Input data for wildfire modeling

168 We assembled data on fuels and topography of the study area in a gridded landscape file as required by FlamMap (Finney 2006), at 25m resolution. Elevation, slope and aspect were 169 170 obtained from 10-m digital elevation data of the island (www.sardegnageoportale.it). Surface 171 and canopy fuels were interpreted from the 2008 Sardinian Land Use Map (Uso del Suolo 172 Regione Sardegna, www.sardegnageoportale.it) following the methodology proposed by Salis et al. 2013. We identified 13 main fuel types, and we then associated to each fuel type 173 174 either a standard or custom model (Table 1, Fig. 3, Anderson 1982; Scott and Burgan 2005; 175 Arca et al. 2009). For forest fuels, we used different fuel models depending on the elevation 176 of the area, using 600 m as threshold of reference. Canopy bulk density, canopy base height 177 and canopy height of the wooded areas were estimated using as reference Quercus suber L. 178 and, at high elevation, Quercus ilex L. stands, considering the data from the National 179 Inventory of Forests and Forest Carbon Sinks (INFC 2005).

180 Fuel moisture content (FMC) for the 1-h and 10-h time lag dead fuel was determined by the 181 methods of Pellizzaro et al. (2005, 2007) and Salis et al. (2015) using several seasons of data, and focusing on the values above the 97th percentile, which reflect conditions commonly 182 183 associated to large wildfires in Sardinia. The main wind direction scenarios were developed 184 from wildfire reports, weather data, and personal communication of the Sardinia Forest 185 Service of the study area. The wind directions mostly related to wildfires in the period 1980-186 2010 were from NW and W, both of which characterized about 65% of days with wildfires. 187 Moreover, large wildfires were observed in days with southern winds (S and SW), which are typically associated to heat waves in the island. About 10% of days with wildfires were 188 characterized by high average wind speed (above 18 km h⁻¹). For the wildfire simulations, 189 wind speed was held constant (35 km h⁻¹) and was derived calculating the wind speed 97th 190

191 percentile, conditions in which containment efforts have little or no effects on fire front192 growth.

Finally, a fire ignition probability grid was developed from the historical database. The ignition probability grid was created with ArcGIS 10.1 (Esri Inc.) using the inverse distance weighting algorithm and a search distance of 1,000 m.

196 *Fuel management scenarios*

197 The fuel management scenarios hypothesized a modification of dead and live fuel 198 characteristics within the treated polygons with respect to the untreated ones. The variation in 199 fuel characteristics after the treatment was fuel-type specific, as reported in Table 1, and was 200 held constant for all scenarios tested. Each fuel treatment alternative originated post-201 treatment scenarios for both surface fuel models, in terms of load, and for canopy fuels, in 202 terms of height to live crown (Table 1): the diverse fuel treatments were used to build 25 x 25 203 m raster input files for wildfire simulations as described below. The treatments reflected 204 moderate fuel management operations (pruning of the lowest branches, removal of dead fuels 205 and part of the understory) in the study area for shrublands, forest understory, and herbaceous 206 pastures (Sardinia Forest Agency, personal communication 2014).

Overall we generated 10 fuel management scenarios, which consisted of the no-treatment 207 208 (NO-TREAT) condition and 9 of scenarios obtained by the combination of 3 treatment intensities with 3 treatment priorities. The diverse fuel treatment intensities constrained the 209 210 total area to 3% (\approx 2,000 ha), 9% (\approx 6,000 ha), and 15% (\approx 10,000 ha) of the landscape (Fig. 211 4). We then applied three spatial treatment priorities, two based on alternative strategies of 212 burn probability (BP) reduction to prioritize protection of urban and anthropic areas (WUI) 213 and roads (ROAD), and the other one based on the selection of random areas (RAND) (Fig. 4). We used a spatial optimization software (LTD, landscape treatment designer (Ager et al. 214

2013; Vogler *et al.* 2015)) to generate optimized fuel management scenarios for WUI and
ROAD, starting from the predicted fire spread and behavior for the no-treatment condition.
The LTD uses inputs on spatial treatment objectives, activity constraints, and treatment
thresholds, and then identifies optimal treatment locations depending on the input parameters
(Vogler *et al.* 2015). The objective function used in this work was to maximize reduction of
BP and FPI nearby WUI and ROAD, using as treatment thresholds a distance between values
and areas treated lower than 1,000 m.

222 The urban and residential protection scenario (WUI) prioritized stands surrounding urban and 223 anthropic areas. Urban and residential areas need to be protected from wildfires, especially for civil protection issues and for protecting values, and often in the Mediterranean basin are 224 225 relevant sources of fire ignitions. Moreover, overall anthropic areas guarantee good accessibility (road network, topography, etc.) to the sites to be treated. A second scenario 226 227 (ROAD) focused on protecting the main roads of the study areas, hypothesizing buffer areas 228 around these values. The road network represents the most relevant fire ignition zone in 229 Sardinia, and also in this case the sites to be treated are easily accessible. We obtained spatial 230 data on urban and anthropic and roads from Regione Sardegna areas 231 (http://www.sardegnageoportale.it/).

Finally, the third fuel treatment scenario (RAND) was based on the identification of randomly located sites in the study area. We first selected a set of points randomly distributed in the territory, which were determined using the "Generate Random Points" command of ArcMap 10.1. From those points, a radius of about 1,230 m was defined in order to treat a total surface of 500 ha per area. The selection of the zones to be treated for the RAND scenario was therefore not linked to any criteria, as well as did not guarantee areas easily accessible for performing the fuel treatments.

239 <u>Wildfire simulations</u>

We used the minimum travel time (MTT) fire spread algorithm of Finney (2002), as implemented in FlamMap (Finney 2006). The MTT algorithm simulates fire growth following the Huygens' principle (Richards 1990; Finney 2002), where fire growth and behavior is modeled as a vector or wave front (Finney 2002; Ager *et al.* 2010). Surface fire spread is predicted following the Rothermel's equation (1972). As previously described, all spatial data required for the simulations (fuels, weather, and topography) were assembled in 25 m resolution binary files.

247 For each treatment alternative, as well as for the untreated landscape, we simulated 25,000 248 wildfires, selecting the ignitions points within burnable fuels of the study area, according to the ignition probability grid developed from the historical database. Simulation parameters 249 250 were developed to reflect likely scenarios associated with escaped large wildfires in the study 251 area based on wildfire history and personal communication with Forest Service and experts. 252 The assumption was that, from a risk standpoint, the primary concern for fire management is 253 the combination of escaped wildfires and extreme weather conditions, since these fires are 254 responsible for the most damage and suppression activities are commonly ineffective against 255 these events (Finney 2005, Calkin et al. 2014). Simulations were performed at 25 m 256 resolution, consistent with the input data, with constant fuel moisture and wind speed (35 km h⁻¹), and a fixed burning period of 10 hours. The four dominant wind directions (NW, W, 257 258 SW, S) associated with the largest fires, with the relative incidence, were used as input as 259 previously defined. No suppression efforts were considered, since their effect in extreme 260 weather days with large fire is overall limited.

The number of fires simulated was adequate to saturate the study area and to ensure that all pixels with burnable fuels were burned more than 200 times on average, and at least once. 263 The wildfire simulations generated a burn probability (BP) and a frequency distribution of 264 flame lengths (FL) in twenty 0.5 m classes for each pixel. The burn probability is the 265 probability a pixel will burn at a given flame length interval, given an ignition in the study 266 area under the assumed weather conditions. The distribution of FL values for each pixel was used to calculate the conditional flame length (CFL), which represents the probability 267 268 weighted flame length given a fire occurs and is a measure of wildfire hazard (Scott 2006). Also, we derived a raster file to evaluate potential fire size, starting from the fire size point 269 270 file and using the inverse distance weighting (search radius 1,000 m) of ArcMap Spatial 271 Analyst. The combination of number of fire ignition points and average fire size for each cell 272 allowed to derive the fire potential index (FPI) (Salis et al. 2013), which measures the 273 potential of a pixel to originate large fires. Crown fire potential occurrence in forest areas was 274 identified for a given pixel and fuel model when the CFL value was higher than the canopy 275 base height value. Moreover, to evaluate the areas where suppression capabilities of 276 terrestrial forces were overwhelmed by fire intensity, we considered 2.5 m as flame length 277 threshold to operate in safety in the fire front (Andrews *et al.* 2011). In addition, a buffer area 278 of 150 m surrounding roads, urban areas and high valued forests was considered to test the 279 performances of fuel treatments nearby the abovementioned highly valued features.

The Kruskal-Wallis non-parametric test was performed to evaluate if there were statistical differences in the medians of BP, CFL, FS and FPI among fuel treatment strategies. We then performed the Bonferroni post-hoc test for pairwise comparison among the treatments.

283 **Results**

284 Effectiveness of fuel treatment strategies on wildfire exposure at landscape scale

The treatment strategies tested in this work decreased average burn probability (BP), conditional flame length (CFL), fire size (FS) and fire potential index (FPI) (Fig. 5 and Table 287 2) with respect to NO-TREAT (Fig. 6); this effect was unequivocal for all the strategies tested, except for CFL on WUI-3% treatment. Furthermore, increasing the percentage of 288 areas treated decreased significantly the average values of BP, CFL, FS and FPI for all fuel 289 treatment strategies (Fig. 5 and Table 2). Average BP among the scenarios and treatment 290 levels ranged from a low of 6.08 10⁻³ with ROAD-15% treatment to a high of 7.61 10⁻³ under 291 RAND-3% treatment, being NO-TREAT equal to 7.71 10⁻³ (Table 2). Likewise, the highest 292 FS and FPI average values were observed in RAND-3% treatment, while the lowest values 293 294 were obtained with ROAD-15% (Table 2). Meanwhile, average CFL reached a maximum of 295 1.137 m under WUI-3% and a minimum of 1.034 m with RAND-15% treatment (Table 2).

As the percentage of the area treated increased, the effectiveness of each strategy on fire 296 297 behavior profiles was enhanced, and this was particularly evident for average BP, FS and FPI 298 (Table 2). Furthermore, random strategy effects in mitigating fire exposure were significantly 299 lower as compared to both urban and road protection (Fig. 7 and Table 2), except for CFL. 300 Applying the treatment to 15% of the areas resulted in a higher reduction of BP, FS and FPI 301 average values for both ROAD and WUI protection strategies (about 20%, 15% and 20%, 302 respectively) (Table 2 and Fig. 7). As far as average CFL is concerned, the differences 303 between strategies were much slighter, although RAND showed the highest percent reduction 304 for both 9% and 15% treatments.

The analysis of variance using the Kruskal-Wallis test indicated highly significant differences (p < 0.01) among fuel treatment strategies for the four wildfire exposure features (Table 2). Among the strategies, regarding BP, only the differences between RND-9% and ROAD-3% were not statistically significant according to the Bonferroni post-hoc test (Table 2). Also, WUI-3% and ROAD-3% were not statistically different with respect to NO-TREAT. The pairwise comparison revealed that FS average values for all treatments were statistically 311 lower with respect to NO-TREAT, while for FPI RAND-3% was not statistically different312 from NO-TREAT.

The fuel treatment strategies resulted in high spatial differences in the four fire exposure features as compared to NO-TREAT condition (Fig. 6) and also among strategies (Fig. 7). Besides, the random strategies resulted in lower differences in BP, FPI and FS as compared with NO-TREAT, while they maximized the differences in terms of CFL (Table 2 and Fig. 6 and 7), mostly due to the spatial arrangement of the areas treated.

318 Effective reductions in the areas potentially affected by crown fires were obtained by 319 applying the diverse fuel treatment strategies (Fig. 8). For each strategy, the spatial 320 distribution of such areas changed and, as the intensity of the treatment increased from 0 to 321 3%, 9% and 15% of the study area, the extent of potential crown fires was limited. The 322 highest reduction in potential crown fires occurrence was obtained with the ROAD strategy 323 (Fig. 8). Moreover, all fire management treatments effectively reduced the number of 324 hectares affected by fires with CFL values higher than 2.5 m, which identified the limit for 325 controlling the fire head by the fire terrestrial forces (Fig. 9). Also, as the intensity of 326 treatment increased, the reduction in the hectares with such conditions was higher, being 327 ROAD strategy the most efficient one, reducing the fires with CFL>2.5 m in about 8%, 14% 328 and 19% with respect to NO-TREAT, respectively when 3%, 9% and 15% of the area were 329 treated. The WUI strategy was the less effective to reduce the hectares of land with CFL 330 values above 2.5 m. When the treatments concerned only 3% of the area, the differences 331 between RAND and ROAD treatments were small (Fig. 9).

332 Effectiveness of fuel treatment strategies on wildfire exposure nearby highly valued features

Overall, the strategies that focused on specific targets (roads and urban areas) were highlyefficient in protecting the neighboring of these values, while random fuel management was

335 less efficient (Fig. 7, 8 and 10). Also in this case, the increase in the area treated induced benefit by reducing the average BP and CFL, as well as the total hectares characterized by 336 337 high fire intensity (average CFL>2.5 m). Furthermore, only in a few cases (with 3% of the 338 total landscape treated), the protection of valued resources was not improved by the 339 treatments with respect to NO-TREAT. Specifically, urban areas neighboring were very 340 efficiently protected by WUI protection strategy (Fig. 10), when the area treated was 9% and 15% of the total landscape, particularly in terms of BP and hectares with CFL>2.5 m: for 341 342 instance, in comparison with NO-TREAT, WUI-15% reduced average BP of about 43%, 343 average CFL of about 25%, and the hectares with CFL>2.5 m of 72%. On the contrary, 344 RAND strategies were inefficient in mitigating fire exposure nearby urban areas (Fig. 10). In 345 the surroundings of roads, ROAD treatments maximized the reduction in exposure factors, 346 although for this target the differences among strategies were less evident than for urban 347 areas protection. In detail, ROAD-15%, which was the best strategy in limiting exposure 348 nearby roads, showed reduction in BP, CFL and hectares with CFL>2.5 m, with respect to 349 NO-TREAT, respectively close to 34%, 19% and 15% (Fig. 10). In terms of protection of the highly valued forests in the study area, even if no specific treatment was designed for 350 351 protection purposes of this target, we observed important benefits in the reduction of the average fire exposure, particularly in terms of BP, with ROAD-9% and mainly ROAD-15%, 352 353 while the other strategies were less adequate (Fig. 10).

354 Influence of fuel types on the effectiveness of fuel treatment strategies

The efficiency in reducing fire exposure varied according to the fuel type (Fig. 11). Grasslands and mixed agricultural areas, although no treatments were considered for these fuel types, benefit from the three strategies tested as shown by average values of BP and CFL (Fig. 11). Generally, an increase in the area treated with all strategies resulted in a reduction 359 of average BP and CFL for all vegetation types. In fact, average CFL was reduced with 360 respect to NO-TREAT by every treatment for all types of vegetation, except for broadleaf 361 forests with WUI-3%, for herbaceous pastures and for Mediterranean maquis, while a 362 decrease in average BP with respect to NO-TREAT was observed for all fuel types. In most cases, ROAD and WUI treatments showed higher effectiveness in reducing average BP 363 364 values as compared with RAND treatments. In broadleaf forests, RAND treatments reduced average CFL as compared to both NO-TREAT and the other fuel treatment strategies. 365 366 Mediterranean maquis showed the highest average fire intensity values among fuel types 367 (CFL ranged from about 2.05 to 2.30 m), while the lowest fire intensity was observed with 368 grasslands (CFL between 0.32 and 0.39 m) (Fig. 11).

369 **Discussion and Conclusions**

370 Quantitative exposure and risk assessment based on wildfire spread models to analyze 371 potential effectiveness of fuel management strategies on losses from wildfires have been 372 presented in many recent papers (Finney 2001, 2006; Ager et al. 2007, 2010, 2013; Finney et 373 al. 2007; Parisien et al. 2007; Miller et al. 2008; Moghaddas et al. 2010; Thompson and 374 Calkin 2011; Liu et al. 2013; Scott et al. 2013; Miller and Ager 2013; Wu et al. 2013). However, the effect of fuel treatment strategies on wildfire exposure and risk has yet to be 375 376 leveraged to improve fuel management and planning in the Mediterranean Basin. This work 377 represents the first application of fire spread modeling methods to quantify tradeoffs from alternative landscape fuel treatment strategies in Mediterranean ecosystems. Our results 378 379 suggests that in Mediterranean areas fuel treatment strategies can potentially reduce average 380 fire exposure (assessed by BP, CFL, FS, and FPI, crown fire potential, and hectares with 381 flame length above 2.5 m). As expected, the effect of the fuel treatments on reducing wildfire 382 exposure increased with the area treated (Ager et al. 2007; Wu et al. 2013). Nevertheless, our study highlights that, when a small percentage of the study area is treated, the effects are localized and not effective at the landscape scale. Yet, from a cost perspective fuel treatments cannot be performed for very large portions of a study area, as the costs of the fuel treatment operations could exceed the benefits of the reduction in losses from wildfires (Schaaf *et al.* 2004; Mercer *et al.* 2008; Thompson *et al.* 2013), depending on the values at risk.

388 Post-treatment changes in forest structure and fuel load can alter wildfire spread and intensity 389 and even increase forest resilience (Graham et al. 2004; Agee and Skinner 2005; Stephens et 390 al. 2012). However, wildfire propagation and behavior are not only governed by fuels, but 391 also by complex relationships among other spatial factors, as for instance topography, wind 392 directions and ignition patterns (Arca et al. 2007; Salis et al. 2013; Wu et al. 2013). The need 393 of protecting specific values from large and destructive wildfires influences the spatial 394 location of fuel treatments and therefore affects the effectiveness of the areas treated in reducing fire threats (Schmidt et al. 2008; Safford et al. 2009; Ager et al. 2010). Our study 395 396 confirmed the existence of tradeoffs among alternative fuel management strategies and the 397 importance of careful prioritization when limited resources are available to manage fuels. We 398 demonstrated that the identification of specific priorities for reducing fire exposure to specific 399 values of interest (e.g.: roads, urban areas, highly valued forests) affects overall landscape 400 protection, including also other targets in the study area. For instance, the goal of protecting 401 urban areas was efficiently addressed by WUI treatment strategy, which at the same time was 402 less effective at limiting fire exposure nearby highly valued forests or the hectares with 403 CFL>2.5 m.

404 Overall, the ROAD protection strategies were the most efficient in reducing average BP, FS 405 and FPI at landscape scale, while RAND treatments maximized average CFL reductions. The 406 latter can be explained by the landscape characteristics and the location of the treatments which, due to the random sampling, were mostly situated in flatter areas than the WUI and
ROAD strategies. In fact, it is well known that terrain slope plays a key role on determining
flame length (Byram 1959; Rothermel 1972; Finney 2002).

410 ROAD strategies also showed the highest performances in both limiting the areas potentially 411 affected by crown fires and the hectares with flame length above 2.5 m, for all treatment 412 intensity tested. The reduction of crown fire occurrence in Mediterranean areas has relevant 413 positive direct and indirect effects on forest mortality and post-fire recovery. For instance, it 414 is proved that oak forests has strong capacity of surviving periodic wildfires and recover 415 quickly the crown, but the likelihood and severity of pests and diseases (e.g.: attacks of 416 defoliators) on weakened resprouting trees is higher (Pausas 1997; Luciano and Roversi 417 2001; Barberis et al. 2003; Branco and Ramos 2009; Catry et al. 2012).

418 The use of the flame length threshold of 2.5 m for effective control efforts of hand tools and 419 equipment in the fire head (Andrews et al. 2011; Alcasena et al. 2015a) coupled with the 420 CFL outputs allowed delineation of the areas where ground-based fire suppression is not 421 feasible for each fuel management strategy. The identification of the most dangerous zones for terrestrial forces may help defining and planning fire management and suppression 422 423 operations (e.g.: prioritizing the use of aerial forces in specific portions of the landscape; 424 optimization of the fire crews distribution in the field), and may inform fuel treatment 425 locations in order to limit the areas that overwhelm terrestrial force suppression capacity. 426 This approach can be very important for wildfire-prone Mediterranean areas, which are frequently characterized by a large spatial variability of fuel types and land uses. 427

The methodology proposed in this paper is adequate to simulate a set of management scenarios and to analyze the performances of fuel treatments using objective measures like burn probability, flame length, or fire size, and may therefore help land management and treatment planning. Moreover, this methodology provides a quantitative framework to analyze losses and benefits from wildfires and to quantify the effectiveness of fuel management options while taking into account wildfire propagation and intensity as well as other exposure profiles. Nevertheless, assessing quantitatively wildfire exposure and risk over large and complex landscapes and evaluating tradeoffs among fuel management strategies remain a challenging issue, since features like socio-economical influences on fire ignitions or fire suppression activities are difficult to be assessed (Ager *et al.* 2010; Calkin *et al.* 2014).

438 The methods and findings of this work can guide the development of strategies to reduce 439 risks posed by large wildfires and to protect values at risk. From this point of view, maps of variation in burn probabilities, conditional flame length or fire potential index after fuel 440 441 treatments can inform land managers about the most efficient options to address wildfire threats. Work is in progress to highlight how and until what extent the diverse Mediterranean 442 443 ecosystems can benefit from fuel treatments. Furthermore, an effort in collecting data and 444 information on the effectiveness of fuel treatments in limiting fire events and on the potential 445 of reducing fuel load and structure is underway to expand this approach to other 446 Mediterranean areas.

In conclusion, we presented a fine scale wildfire exposure assessment framework, based on the MTT fire spread algorithm (Finney 2002), that incorporated the complex interactions among wildfire spread and behavior, topography, fuels and weather, and highlighted how and how much fuel treatment strategies may influence wildfire exposure and losses for a study area in North Sardinia (Italy). This methodology allowed to quantify with an objective approach the tradeoffs posed by diverse strategies of fuel treatments, and to provide guidelines and suggestions for land managers. This work increases knowledge on main

- 454 critical points of fire exposure and management, and thus may help defining and optimizing
- 455 the strategies and spatial location of fuel treatments.

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764 <u>www.centrometeo.com</u>

765 <u>www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp</u>

- 766 <u>www.sardegnageoportale.it</u>
- 767 <u>www.tutiempo.es</u>
- 768 <u>www.wunderground.com</u>
- 769
- 770
- 771

- 1 Table 1. Fuel model data used for the wildfire simulations. A different combination of fuel
- 2 models was used depending on elevation (ELEV) and fuel treatment activity (TREAT). CH =
- 3 canopy height; CBD = canopy bulk density; CBH = canopy base height.

FUEL MODEL CODE	FUEL DEAD LOAD	FUEL LIVE LOAD	FUEL DEPTH	DESCRIPTION	ELEV	TREAT	СН	CBD	СВН
	(t ha ⁻¹)	$(t ha^{-1})$	(cm)				(m)	$(100* \text{ kg m}^{-3})$	(m)
FM25	1.2	0.0	20	Grasslands			0	0	0
FM26	1.2	0.0	30	Mix Agricultural Areas			0	0	0
FM27	1.0	2.0	80	Orchards			10	11	1
FM28	2.5	0.0	35	Herbaceous Pastures	m 006	ated	0	0	0
FM29	5.3	4.1	45	Garrigue	5 MO	ntre	0	0	0
FM30	15.0	12.5	135	Mediterranean Maquis	bel	N	12	14	1
FM31	10.0	1.0	25	Conifer			14	11	2
FM32	12.0	2.0	70	Broadleaf			12	14	2
FM33	12.0	2.0	70	Mixed Forests			14	13	2
FM45	1.2	0.0	20	Grasslands			0	0	0
FM46	1.2	0.0	30	Mix Agricultural Areas			0	0	0
FM47	1.0	2.0	80	Orchards			10	11	1
FM48	3.0	0.0	35	Herbaceous Pastures	ш 00é	sated	0	0	0
FM49	6.4	4.9	70	Garrigue	ove 9	ntre	0	0	0
FM50	18.0	15.0	160	Mediterranean Maquis	abc		12	14	1
FM51	12.0	1.2	25	Conifer			15	11	4
FM52	14.4	2.4	70	Broadleaf			14	14	3
FM53	14.4	2.4	70	Mixed Forests			15	13	4
FM65	1.2	0.0	20	Grasslands			0	0	0
FM66	1.2	0.0	30	Mix Agricultural Areas			0	0	0
FM67	1.0	2.0	80	Orchards			10	10	2
FM68	1.2	0.0	35	Herbaceous Pastures	m 006	ted	0	0	0
FM69	2.5	3.5	45	Garrigue	6 MO	Irea	0	0	0
FM70	4.5	11.0	135	Mediterranean Maquis	bel	L	12	13	2
FM71	5.0	1.0	25	Conifer			14	10	3
FM72	5.0	2.0	70	Broadleaf			12	13	3
FM73	5.0	2.0	70	Mixed Forests			14	12	3
FM85	1.2	0.0	20	Grasslands			0	0	0
FM86	1.2	0.0	30	Mix Agricultural Areas	00 m	eq	0	0	0
FM87	1.0	2.0	80	Orchards	ve 9	reat	10	10	2
FM88	1.2	0.0	35	Herbaceous Pastures	abo	L	0	0	0
FM89	2.5	3.5	70	Garrigue			0	0	0

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FM90	4.5	13.0	160	Mediterranean Maquis		12	13	2
FM91	5.0	1.0	25	Conifer		15	10	5
FM92	5.0	2.0	70	Broadleaf		14	13	4
FM93	5.0	2.0	70	Mixed Forests		15	12	5

Table 2. Summary of the mean values and standard deviation (under parenthesis) of burn probability (BP), conditional flame length (CFL), fire size (FS) and fire potential index (FPI) for the diverse fuel treatment strategies. The Kruskal-Wallis one-way ANOVA test (p < 0.05) was performed to evaluate statistical differences in fire exposure indicators among fuel treatments. The Bonferroni post-hoc test for pairwise comparison among the treatments was then performed.

FUEL TREATMENT STRATEGY	BP	CFL (m)	FS (ha)	FPI
NO TREAT	7.71E-03a	1.125ab	564.88a	531.43a
NO-IKEAI	(8.28E-03)	(0.825)	(472.09)	(564.44)
PAND 20/	7.61E-03b	1.097cd	559.82b	526.53a
KAND-3 %	(8.29E-03)	(0.823)	(475.51)	(568.80)
PAND 00/	7.11E-03d	1.065e	531.55d	494.03c
KAND-976	(7.77E-03)	(0.818)	(464.42)	(539.37)
PAND 15%	6.84E-03e	1.034f	501.56f	472.22d
KAND-1370	(7.61E-03)	(0.812)	(448.34)	(523.41)
POAD 3%	7.06E-03d	1.124b	540.04c	488.61c
ROAD-3%	(7.57E-03)	(0.822)	(464.45)	(515.26)
R01D-0%	6.35E-03g	1.091d	501.66f	435.26f
KOAD-770	(6.86E-03)	(0.813)	(441.38)	(454.48)
ROAD 15%	6.08E-03i	1.065e	472.05h	410.49h
KOAD-1570	(6.74E-03)	(0.803)	(407.64)	(437.21)
WI/I_3%	7.31E-03c	1.137a	553.80b	507.74b
W01-570	(7.69E-03)	(0.830)	(471.38)	(534.19)
W171_0%	6.66E-03f	1.104c	513.35e	455.31e
W01-970	(7.11E-03)	(0.819)	(440.48)	(473.02)
WIII_15%	6.21E-03h	1.076e	481.80g	424.62g
W01-1370	(6.81E-03)	(0.807)	(416.96)	(444.03)
Group comparison (Kruskal-Wallis test, p-value)	0.001	0.001	0.001	0.001

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

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Fi	g	u	re	3
	-		-	-

OBJECTID	GIORNO	MESE		FN		%FN	AB	%FN
575	18	6	≤0.1		486	62.70968	8.28	0.184014
760	21	6	0.1-1		149	19.22581	86.19	1.915482
214	22	6	1-10		105	13.54839	372.18	8.27131
579	23	6	10-100		28	3.612903	945.00	21.00163
539	1	7	>100		7	0.903226	3088.00	68.62756
553	3	7	TOTALE		775		4499.65	
554	3	7			25		145.15	
582	3	7						
215	4	7						
540	5	7						
555	5	7						
583	6	7						
216	8	7						
217	8	7						
218	9	7						
219	10	7						
558	10	7						
584	10	7						
220	11	7						
585	12	7						
221	13	7						
222	14	7						
542	15	7						
223	16	7						
224	18	7						
274	18	7						
358	18	7						
448	18	7						
225	19	7						
226	19	/						
275	19	/						
586	19	/						
1/8	20	/						
301	20	/						
14	21	/						
15 727	21	/						
227	21	/ 7						
2/0	21	/ 7						
545 วาง	21	/ 7						
220	22	י ר						
573 773	25 25	י ר						
202 //EU	25 72	י ד						
430 220	23 24	י ד						
230	24	י ד						
366	24	, 7						
500	24	/						







	0%	3%	9%	15%	
NO-TREAT	0.00771				
RAND		0.00761	0.00711	0.00684	BP
ROAD		0.00706	0.00635	0.00608	
WUI		0.00731	0.00666	0.00621	
	0%	3%	9%	15%	
NO-TREAT	1.12523				
RAND		1.0967	1.06513	1.03448	CFL
ROAD		1.12397	1.09108	1.06485	
WUI		1.13678	1.10426	1.07555	
	0%	3%	9%	15%	
NO-TREAT	228.778				
RAND		226.729	215.279	203.131	FS
ROAD		218.717	203.17	191.18	
WUI		224.289	207.907	195.128	
	0%	3%	9%	15%	
NO-TREAT	215.229				
RAND		213.244	200.08	191.251	FPI
ROAD		197.888	176 28	166 2/18	
			170.20	100.240	
WUI		205.634	184.401	171.972	
WUI		205.634	184.401	171.972	
WUI		205.634	184.401	171.972	
WUI	0%	205.634 3%	184.401 9%	171.972 15%	
WUI NO-TREAT	0% 564.884	205.634 3%	184.401 9%	171.972 15%	
WUI NO-TREAT RAND	0% 564.884	205.634 3% 559.824	184.401 9% 531.554	171.972 175%	FS
WUI NO-TREAT RAND ROAD	0% 564.884	205.634 3% 559.824 540.041	184.401 9% 531.554 501.655	100.240 171.972 15% 501.558 472.05	FS
WUI NO-TREAT RAND ROAD WUI	0% 564.884	205.634 3% 559.824 540.041 553.8	9% 531.554 501.655 513.351	100.240 171.972 15% 501.558 472.05 481.798	FS
WUI NO-TREAT RAND ROAD WUI	0% 564.884	205.634 3% 559.824 540.041 553.8	184.401 9% 531.554 501.655 513.351	100.240 171.972 15% 501.558 472.05 481.798	FS
WUI NO-TREAT RAND ROAD WUI	0% 564.884 0%	205.634 3% 559.824 540.041 553.8 3%	9% 531.554 501.655 513.351 9%	100.240 171.972 15% 501.558 472.05 481.798 15%	FS
WUI NO-TREAT ROAD WUI NO-TREAT	0% 564.884 0% 531.43	205.634 3% 559.824 540.041 553.8 3%	9% 531.554 501.655 513.351 9%	100.240 171.972 15% 501.558 472.05 481.798 15%	FS
WUI NO-TREAT RAND ROAD WUI NO-TREAT RAND	0% 564.884 0% 531.43	205.634 3% 559.824 540.041 553.8 3% 526.529	184.401 9% 531.554 501.655 513.351 9% 494.026	100.240 171.972 15% 501.558 472.05 481.798 15% 472.225	FS
WUI NO-TREAT RAND ROAD WUI NO-TREAT RAND ROAD	0% 564.884 0% 531.43	205.634 3% 559.824 540.041 553.8 3% 526.529 488.613	184.401 9% 531.554 501.655 513.351 9% 494.026 435.259	100.240 171.972 15% 501.558 472.05 481.798 15% 472.225 410.489	FS























	HECTARES CFL>2.5					
Т0	6191.00					
RAND-3%	5734.75					
RAND-9%	5410.00					
RAND-15%	5151.00					
ROAD-3%	5690.75					
ROAD-9%	5320.00					
ROAD-15%	5046.00					
WUI-3%	6006.00					
WUI-9%	5585.00					
WUI-15%	5259.50					
0%						
3%						
9%						
15%						

URBAN

	PBurn	CFL	ha	PBurn	CFL	ha		PBurn
NO-TREAT	0.006474086	0.77	224 NO-TREAT	0.006474086	0.77		NO-TREAT	0.006474086
RAND-3%	0.006355645	0.76	201.5 ROAD-3%	0.006316932	0.77	217.5	WUI-3%	0.00576039
RAND-9%	0.006209632	0.75	194.25 ROAD-9%	0.005339096	0.73	183	WUI-9%	0.00444655
RAND-15%	0.006083916	0.74	185 ROAD-15%	0.005171687	0.71	174	WUI-15%	0.003707543

FORESTS

	PBurn	CFL	ha	PBurn	CFL	ha		PBurn
NO-TREAT	0.018364124	1.62	80.25 NO-TREAT	0.018364124	1.62		NO-TREAT	0.018364124
RAND-3%	0.017300944	1.61	83 ROAD-3%	0.014835522	1.54	72.5	WUI-3%	0.016277063
RAND-9%	0.015283658	1.44	76.75 ROAD-9%	0.012200917	1.34	67.5	WUI-9%	0.015551609
RAND-15%	0.015744963	1.44	76.5 ROAD-15%	0.010937111	1.20	63	WUI-15%	0.014651726

ROADS

	PBurn	CFL	ha	PBurn	CFL	ha	PBurn
NO-TREAT	0.009173	1.14	140.5 NO-TREAT	0.009173	1.14	140.5 NO-TREAT	0.009173
RAND-3%	0.00889781	1.12	135.25 ROAD-3%	0.00853089	1.04	131.5 WUI-3%	0.00953992
RAND-9%	0.00807224	1.09	132.25 ROAD-9%	0.00687975	0.97	128.5 WUI-9%	0.007086143
RAND-15%	0.0073384	1.08	130 ROAD-15%	0.006050511	0.92	120 WUI-15%	0.006776572

		NO-T	ROAD-3%				
FUEL	BP_avg	CFL_avg	FS_avg	FPI_avg	BP_avg	CFL_avg	FS_avg
Pastures	0.00892006	0.927771	227.3391866	247.8566	0.00867	0.757382	222.2567
Garrigue	0.011306844	1.415257	321.9731628	273.3325	0.010843	1.299297	318.4239
Mediterranean Maquis	0.012799088	2.058522	369.090345	337.8865	0.011297	2.265919	347.9497
Conifer	0.007527509	1.110284	222.6053429	211.8751	0.006541	0.898353	208.0381
Broadleaf	0.005844558	0.882382	191.5840959	183.2867	0.005366	0.871819	183.1919

1 Evaluating alternative fuel treatment strategies to reduce wildfire losses in a



2 Mediterranean area

3

4 Fig.1. Digital elevation model (DEM) of the study area along with roads, urban and anthropic
5 areas (UA), and highly valued forests (HVF).

6

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8

9 Fig. 2. Main fuel types of the study area. UA=urban and anthropic areas; W=water bodies;

- 10 R=rocks; S=sands; GR=grasslands; MA=mixed agricultural areas; VO=vineyards and
- 11 orchards; HP=herbaceous pastures; G=garrigue; MM=Mediterranean maquis; CF=conifer
- 12 forests; BF=broadleaf forests; MF= mixed forests





15 Fig. 3. Percentage of area burned and fire number per fire size class in the study area

16 (Sardinia Forest Service, data from 1980 to 2010)



Fig. 4. Maps of the fuel treatment strategies tested (random treatments (RAND, a, b, c), road protection (ROAD, d, f, g), urban and anthropic areas protection (WUI, g, h, i)), considering 3%, 9% and 15% of the landscape treated.

26



Fig. 5. Effect of fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI) and treatment
intensity (3%, 9%, 15%) on average burn probability (BP, a), conditional flame length (CFL,
b), fire size (FS, c) and fire potential index (FPI, d). This analysis was performed considering
the whole landscape.

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- 39 Fig. 6. Burn probability (BP, a), conditional flame length (CFL, b), fire size (FS, c), and fire
- 40 potential index (FPI, d) for the untreated scenario (NO-TREAT).
- 41
- 42





47 Fig. 7. Differences in BP (a, b, c), CFL (d, e, f), FS (g, h, i) and FPI (j, k, l) between the fuel
48 treatment strategies (RAND, ROAD and WUI, considering the treatment intensity of 15%)
49 and the untreated condition (NO-TREAT).



Fig. 8. Potential crown fire (CF) occurrence considering the diverse strategies (NO-TREAT,
a; RAND, b; ROAD, c; WUI, d). The areas with different blue color gradations, from light to
dark, indicate the reduction of crown fires associated with increasing treatment intensities
(3%, 9%, 15% of the landscape treated).



Fig. 9. Effect of fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI) and treatment
intensities on the number of hectares with CFL values above 2.5 m.



Fig. 10. Scatterplots of BP vs. CFL and BP vs. hectares with CFL>2.5 m in the surroundings
(buffer 150 m) of urban areas (a, b), roads (c, d), and highly valued forests (e, f).





Fig. 11. Scatterplots of average BP vs average CFL (left) and average BP vs average FPI (right) for the main vegetation types (broadleaf forests, a, b; Mediterranean maquis, c, d; conifer forests, e, f; garrigue, g, h; herbaceous pastures, i, j) of the study area, considering all the fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI)