

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

Questa è la versione Post print del seguente articolo:

Original

Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area / Salis, Michele; Laconi, Maurizio; Ager, Alan A.; Alcasena, Fermin J.; Arca, Bachisio; Lozano, Olga; Fernandes de Oliveira, A; Spano, Donatella. - In: FOREST ECOLOGY AND MANAGEMENT. - ISSN 0378-1127. - 368:(2016), pp. 207-221. [10.1016/j.foreco.2016.03.009]

Availability:

This version is available at: 11388/199968 since: 2018-03-28T13:26:41Z

Publisher:

Published

DOI:10.1016/j.foreco.2016.03.009

Terms of use:

Chiunque può accedere liberamente al full text dei lavori resi disponibili come "Open Access".

Publisher copyright

note finali coverpage

(Article begins on next page)

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

3 Michele Salis^{1,2}, Maurizio Laconi³, Alan A. Ager⁴, Fermin J. Alcasena⁵, Bachisio Arca⁶, Olga
4 Lozano¹, Ana Fernandes de Oliveira⁷, Donatella Spano^{1,2}

5 ¹ *University of Sassari, Department of Science for Nature and Environmental Resources (DIPNET),*
6 *Via De Nicola 9, 07100, Sassari (Italy), e-mail: miksalis@uniss.it*

7 ² *Euro-Mediterranean Center on Climate Change (CMCC), IAFES Division, Via De Nicola 9, 07100,*
8 *Sassari (Italy)*

9 ³ *Former student of the Master “PIROS”, University of Sassari, Department of Science for Nature*
10 *and Environmental Resources (DIPNET), Via De Nicola 9, 07100, Sassari (Italy)*

11 ⁴ *USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775*
12 *US Highway 10W, Missoula, MT 59808 (USA)*

13 ⁵ *University of Lleida, Department of Agricultural and Forest Engineering, Avenida da Rovira Roure*
14 *191, 25198 Lleida, Spain*

15 ⁶ *National Research Council (CNR), Institute of Biometeorology (IBIMET), Traversa La Crucca 3,*
16 *07100, Sassari (Italy)*

17 ⁷ *University of Sassari, Department of Agriculture, Via De Nicola 9, 07100, Sassari (Italy)*

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
24 MTT fire spread algorithm. The simulations replicated severe wildfires observed around the
25 study area, using historic weather and fuel moisture conditions (97th percentile). Wildfire
26 exposure profiles for the study area as a whole and for locations with specific values of
27 interest were analyzed. Results indicated significant variations in wildfire exposure among
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
36 management effectiveness on wildfire risk mitigation in the Mediterranean areas.

37 **Keywords**

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

40 **Introduction**

41 Wildfires represent a substantial threat to Southern European forests and ecosystems and
42 every year cause extensive losses to anthropic infrastructures and values (Bassi *et al.* 2008;
43 San-Miguel-Ayanz *et al.* 2013; Schmuck *et al.* 2014). Although the economic investments in
44 fire suppression and fire crews training and preparation have progressively increased during
45 the last decades, large wildfires still overwhelm suppression capabilities, spread for large
46 distances and burn thousands of hectares (Costa Alcobierre *et al.* 2011; Alcasena *et al.*

47 2015b). Wildfire spread during these events represents the primary contributor to wildfire
48 losses and area burned (Ganteaume and Jappiot 2013; Salis *et al.* 2013). Mega-fires usually
49 occur under extreme weather conditions, such as strong winds, low relative humidity and
50 prolonged drought (Trigo *et al.* 2006; Viegas *et al.* 2009; Koutsias *et al.* 2012; Pausas and
51 Fernandez-Munoz 2012; Cardil *et al.* 2013, 2014; Salis *et al.* 2014).

52 Humans play a key role on influencing fire regimes, by means of anthropic fire ignitions,
53 implementation of socio-economic policies and land uses, and fire suppression activities
54 (Moreira *et al.* 2011). In the Mediterranean Basin, more than 90% of fire ignitions are
55 human-caused and follow complex spatio-temporal patterns related to anthropic and
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
63 expansion in shrubby, thicket fuels on previously marginal and rural lands, as well as the
64 development of understory vegetation and ladder fuels in previous timber production areas
65 (Pausas 2004; Bonet and Pausas 2007; Ruiz-Mirazo *et al.* 2012). The result was a transition
66 from mosaic-managed type landscapes to a high fuel load, continuous and highly hazardous
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
69 growing incidence of intense and large wildfires (Badia *et al.* 2002; Pinol *et al.* 2005;
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
78 wilderness and unmanaged lands, and thus managing wildfires for fuel management poses
79 unacceptable risks (Lampin-Maillet *et al.* 2010; Pellizzaro *et al.* 2012; Moritz *et al.* 2014).
80 Fuel management strategies employ a combination of surface fuel loading, depth and
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
89 budget (Parisien *et al.* 2007; Reinhardt *et al.* 2008; Ager *et al.* 2013; Hand *et al.* 2014;
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,
96 and quantified the capabilities of fuel treatments in reducing losses from fires for specific

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

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

121 Importance (EU 92/43/EEC Directive). The territory is mainly characterized by the granitic
122 mountain complex of Monte Limbara, with orientation SW-NE, and by the Coghinas lake,
123 the largest one of North Sardinia. The elevation of the study area ranges from about 45 m
124 a.s.l. to the highest point of Punta Balistreri (about 1,350 m a.s.l.). Overall, the area is
125 characterized by a complex topography, and about 25% of the land is above 600 m a.s.l. (Fig.
126 1).

127 The climate is Mediterranean, with hot and dry summers and cold and wet winters, and
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 to the top of 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
141 degraded areas. The conifer woods occupy limited areas, and are mainly represented by
142 artificial plantations of *Pinus pinea* L., *Pinus pinaster* Aiton, and *Pinus nigra* ssp. *laricio*
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

145 ha of land, being the town and the industrial area of Tempio Pausania the most relevant
146 anthropic zone of the study site. Fruit-bearing areas are mostly represented by sparse and
147 family-farm vineyards and olive groves and cover about 2,300 ha of land; these land types are
148 largely concentrated in flat areas and nearby the town of Tempio Pausania. Grasslands and
149 agricultural areas are mainly devoted to herbaceous and horticultural productions and
150 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
153 provided by the Sardinia Forest Service. This database collects information on ignition points
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
156 concentrated in four months, from June to September, and about 60% of the events happened
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.

162 To examine the weather conditions of the days with fire occurrence in the study area, we
163 gathered daily meteorological data from the weather stations of Olbia and Alghero (North
164 Sardinia) and from the reports of the Sardinia Forest Service (Sardinia Forest Service,
165 personal communication 2014; www.tutiempo.es; www.centrometeo.com;
166 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
169 required by FlamMap (Finney 2006), at 25m resolution. Elevation, slope and aspect were
170 obtained from 10-m digital elevation data of the island (www.sardegnoportale.it). Surface
171 and canopy fuels were interpreted from the 2008 Sardinian Land Use Map (Uso del Suolo
172 Regione Sardegna, www.sardegnoportale.it) following the methodology proposed by
173 Salis *et al.* 2013. We identified 13 main fuel types, and we then associated to each fuel type
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,
182 and focusing on the values above the 97th percentile, which reflect conditions commonly
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
188 typically associated to heat waves in the island. About 10% of days with wildfires were
189 characterized by high average wind speed (above 18 km h⁻¹). For the wildfire simulations,
190 wind speed was held constant (35 km h⁻¹) and was derived calculating the wind speed 97th

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

193 Finally, a fire ignition probability grid was developed from the historical database. The
194 ignition probability grid was created with ArcGIS 10.1 (Esri Inc.) using the inverse distance
195 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).

207 Overall we generated 10 fuel management scenarios, which consisted of the no-treatment
208 (NO-TREAT) condition and 9 of scenarios obtained by the combination of 3 treatment
209 intensities with 3 treatment priorities. The diverse fuel treatment intensities constrained the
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.
214 4). We used a spatial optimization software (LTD, landscape treatment designer (Ager *et al.*

215 2013; Vogler *et al.* 2015)) to generate optimized fuel management scenarios for WUI and
216 ROAD, starting from the predicted fire spread and behavior for the no-treatment condition.
217 The LTD uses inputs on spatial treatment objectives, activity constraints, and treatment
218 thresholds, and then identifies optimal treatment locations depending on the input parameters
219 (Vogler *et al.* 2015). The objective function used in this work was to maximize reduction of
220 BP and FPI nearby WUI and ROAD, using as treatment thresholds a distance between values
221 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
224 for civil protection issues and for protecting values, and often in the Mediterranean basin are
225 relevant sources of fire ignitions. Moreover, overall anthropic areas guarantee good
226 accessibility (road network, topography, etc.) to the sites to be treated. A second scenario
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 areas and roads from Regione Sardegna
231 (<http://www.sardegnaoportale.it/>).

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

239 Wildfire simulations

240 We used the minimum travel time (MTT) fire spread algorithm of Finney (2002), as
241 implemented in FlamMap (Finney 2006). The MTT algorithm simulates fire growth
242 following the Huygens' principle (Richards 1990; Finney 2002), where fire growth and
243 behavior is modeled as a vector or wave front (Finney 2002; Ager *et al.* 2010). Surface fire
244 spread is predicted following the Rothermel's equation (1972). As previously described, all
245 spatial data required for the simulations (fuels, weather, and topography) were assembled in
246 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
249 the ignition probability grid developed from the historical database. Simulation parameters
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
257 h⁻¹), and a fixed burning period of 10 hours. The four dominant wind directions (NW, W,
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.

261 The number of fires simulated was adequate to saturate the study area and to ensure that all
262 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
267 used to calculate the conditional flame length (CFL), which represents the probability
268 weighted flame length given a fire occurs and is a measure of wildfire hazard (Scott 2006).
269 Also, we derived a raster file to evaluate potential fire size, starting from the fire size point
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.

280 The Kruskal-Wallis non-parametric test was performed to evaluate if there were statistical
281 differences in the medians of BP, CFL, FS and FPI among fuel treatment strategies. We then
282 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*

285 The treatment strategies tested in this work decreased average burn probability (BP),
286 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
288 tested, except for CFL on WUI-3% treatment. Furthermore, increasing the percentage of
289 areas treated decreased significantly the average values of BP, CFL, FS and FPI for all fuel
290 treatment strategies (Fig. 5 and Table 2). Average BP among the scenarios and treatment
291 levels ranged from a low of $6.08 \cdot 10^{-3}$ with ROAD-15% treatment to a high of $7.61 \cdot 10^{-3}$ under
292 RAND-3% treatment, being NO-TREAT equal to $7.71 \cdot 10^{-3}$ (Table 2). Likewise, the highest
293 FS and FPI average values were observed in RAND-3% treatment, while the lowest values
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).

296 As the percentage of the area treated increased, the effectiveness of each strategy on fire
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.

305 The analysis of variance using the Kruskal-Wallis test indicated highly significant differences
306 ($p < 0.01$) among fuel treatment strategies for the four wildfire exposure features (Table 2).
307 Among the strategies, regarding BP, only the differences between RND-9% and ROAD-3%
308 were not statistically significant according to the Bonferroni post-hoc test (Table 2). Also,
309 WUI-3% and ROAD-3% were not statistically different with respect to NO-TREAT. The
310 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 different
312 from NO-TREAT.

313 The fuel treatment strategies resulted in high spatial differences in the four fire exposure
314 features as compared to NO-TREAT condition (Fig. 6) and also among strategies (Fig. 7).
315 Besides, the random strategies resulted in lower differences in BP, FPI and FS as compared
316 with NO-TREAT, while they maximized the differences in terms of CFL (Table 2 and Fig. 6
317 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*

333 Overall, the strategies that focused on specific targets (roads and urban areas) were highly
334 efficient 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
336 benefit by reducing the average BP and CFL, as well as the total hectares characterized by
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
341 15% of the total landscape, particularly in terms of BP and hectares with CFL>2.5 m: for
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
350 highly valued forests in the study area, even if no specific treatment was designed for
351 protection purposes of this target, we observed important benefits in the reduction of the
352 average fire exposure, particularly in terms of BP, with ROAD-9% and mainly ROAD-15%,
353 while the other strategies were less adequate (Fig. 10).

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

355 The efficiency in reducing fire exposure varied according to the fuel type (Fig. 11).
356 Grasslands and mixed agricultural areas, although no treatments were considered for these
357 fuel types, benefit from the three strategies tested as shown by average values of BP and CFL
358 (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
363 cases, ROAD and WUI treatments showed higher effectiveness in reducing average BP
364 values as compared with RAND treatments. In broadleaf forests, RAND treatments reduced
365 average CFL as compared to both NO-TREAT and the other fuel treatment strategies.
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).
375 However, the effect of fuel treatment strategies on wildfire exposure and risk has yet to be
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
378 alternative landscape fuel treatment strategies in Mediterranean ecosystems. Our results
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

383 study highlights that, when a small percentage of the study area is treated, the effects are
384 localized and not effective at the landscape scale. Yet, from a cost perspective fuel treatments
385 cannot be performed for very large portions of a study area, as the costs of the fuel treatment
386 operations could exceed the benefits of the reduction in losses from wildfires (Schaaf *et al.*
387 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
395 reducing fire threats (Schmidt *et al.* 2008; Safford *et al.* 2009; Ager *et al.* 2010). Our study
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

407 which, due to the random sampling, were mostly situated in flatter areas than the WUI and
408 ROAD strategies. In fact, it is well known that terrain slope plays a key role on determining
409 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
422 for terrestrial forces may help defining and planning fire management and suppression
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
427 frequently characterized by a large spatial variability of fuel types and land uses.

428 The methodology proposed in this paper is adequate to simulate a set of management
429 scenarios and to analyze the performances of fuel treatments using objective measures like
430 burn probability, flame length, or fire size, and may therefore help land management and

431 treatment planning. Moreover, this methodology provides a quantitative framework to
432 analyze losses and benefits from wildfires and to quantify the effectiveness of fuel
433 management options while taking into account wildfire propagation and intensity as well as
434 other exposure profiles. Nevertheless, assessing quantitatively wildfire exposure and risk over
435 large and complex landscapes and evaluating tradeoffs among fuel management strategies
436 remain a challenging issue, since features like socio-economical influences on fire ignitions
437 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
440 variation in burn probabilities, conditional flame length or fire potential index after fuel
441 treatments can inform land managers about the most efficient options to address wildfire
442 threats. Work is in progress to highlight how and until what extent the diverse Mediterranean
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.

447 In conclusion, we presented a fine scale wildfire exposure assessment framework, based on
448 the MTT fire spread algorithm (Finney 2002), that incorporated the complex interactions
449 among wildfire spread and behavior, topography, fuels and weather, and highlighted how and
450 how much fuel treatment strategies may influence wildfire exposure and losses for a study
451 area in North Sardinia (Italy). This methodology allowed to quantify with an objective
452 approach the tradeoffs posed by diverse strategies of fuel treatments, and to provide
453 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.

456 **Acknowledgements**

457 This work was funded by several sources including the “GEMINA” Project (MIUR/MATTM
458 no. 232/2011), the “Extreme” Project (Sardinia Reg., CRP-25405, LR 7/2007), the “Sughera”
459 Project (Sardinia Reg., Tender 2013 LR 7/2007) and the “Modeling approach to evaluate fire
460 risk and mitigation planning actions” Project (POR SARDEGNA FSE 2007–2013, Asse IV
461 Capitale umano, Linea di Attivita` 1.3.1).

462 **References**

- 463 Ager JK (2002) The fallacy of passive management managing for firesafe forest
464 reserves. *Conservation in Practice* 3: 18–26
- 465 Ager JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments.
466 *Forest Ecology and Management* 211: 83–96
- 467 Ager AA, Preisler H, Arca B, Spano D, Salis M (2014a) Wildfire risk estimation in the
468 Mediterranean area. *Environmetrics* 25(6): 384–396
- 469 Ager AA, Finney MA, Kerns BK, Maffei H (2007) Modeling wildfire risk to northern
470 spotted owl (*Strix occidentalis caurina*) habitat in Central Oregon, USA. *Forest Ecology and*
471 *Management* 246: 45–56
- 472 Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment
473 strategies to mitigate wildland fire risk in the urban interface and preserve old forest
474 structure. *Forest Ecology and Management* 259(8): 1556–1570
- 475 Ager AA, Vaillant NM, McMahan A (2013) Restoration of fire in managed forests: a
476 model to prioritize landscapes and analyze tradeoffs. *Ecosphere* 4(2): 29.
- 477 Alcasena FJ, Salis M, Ager AA, Arca B, Molina D, Spano D (2015a) Assessing
478 Landscape Scale Wildfire Exposure for Highly Valued Resources in a Mediterranean Area.
479 *Environmental Management* 55(5): 1200-1216
- 480 Alcasena FJ, Salis M, Vega-Garcia C (2015) A fire modeling approach to assess
481 wildfire exposure in central Navarra, Spain. *European Journal of Forest Research* 135: 87-
482 107.
- 483 Anderson HE (1982) Aids to determining fuel models for estimating fire behaviour.
484 USDA Forest Service, Intermountain Forest and Range Experiment Station, General
485 Technical Report INT-GTR-122

486 Andrews PL, Heinsch FA, Schelvan L (2011) How to generate and interpret fire
487 characteristics charts for surface and crown fire behavior. General Technical Report RMRS-
488 GTR-253. USDA Forest Service, Rocky Mountain Research Station, Fort Collins

489 Arca B, Bacciu V, Pellizzaro G, Salis M, Ventura A, Duce P, Spano D, Brundu G
490 (2009) Fuel model mapping by IKONOS imagery to support spatially explicit fire simulators.
491 In '7th international workshop on advances in remote sensing and GIS applications in forest
492 fire management towards an operational use of remote sensing in forest fire management.'
493 (Matera, Italy)

494 Arrigoni PV (1968) Fitoclimatologia della Sardegna. *Webbia* 23: 1-100

495 Barberis A, Dettori S, Filigheddu MR (2003) Management problems in Mediterranean
496 cork oak forests: post-fire recovery. *Journal of Arid Environments* 54: 565–569

497 Badia A, Sauri D, Cerdan R, Llurdés J-C (2002) Causality and management of forest
498 fires in Mediterranean environments: an example from Catalonia. *Environmental Hazards* 4:
499 23–32

500 Bassi S, Kettunen M, Kampa E, Cavalieri S (2008). Forest fires: causes and
501 contributing factors to forest fire events in Europe. Study for the European Parliament
502 Committee on environment, public health and food safety, under contract
503 IP/A/ENVI/FWC/206-172/LOTI/C1/SC10
504 http://www.ieep.eu/assets/392/forest_fires_report.pdf

505 Bonet A, Pausas JG (2007) Old field dynamics on the dry side of the Mediterranean
506 Basin: patterns and processes in semiarid SE Spain. In: Cramer VA, Hobbs RJ (eds) Old
507 fields dynamics and restoration of abandoned farmland. Island Press, Washington, DC, pp
508 247–264

509 Bovio G (2002) La pianificazione antincendi boschivi. In Anfodillo T, Carraro V (eds.),
510 Il fuoco in foresta: ecologia e controllo. Pubblicazione del Corso di Cultura in Ecologia, Atti
511 del 39° Corso, Università di Padova, pp 1-14

512 Bovio G, Ascoli D (2013) La tecnica del fuoco prescritto. 272 pp. ISBN 978-88-548-
513 6305-7. ARACNE editrice, Roma, Italy

514 Branco M, Ramos P (2009) Coping with pests and diseases. In Aronson J, Pereira JS,
515 Pausas JG (eds) Cork oak woodlands on the edge: conservation, adaptive management, and
516 restoration. Pag. 103-111. Island Press, Washington, DC.

517 Byram GM (1959) Combustion of forest fuels. In: Davis KP (ed) Forest Fire: Control
518 and Use. McGraw-Hill, New York, pp. 61–89

519 Calkin DE, Gebert KM, Jones JG, Neilson RP (2005) Forest service large fire area
520 burned and suppression expenditure trends, 1970-2002. *Journal of Forestry* 103(4): 179-183

521 Calkin DE, Cohen JD, Finney MA, Thompson MP (2014) How risk management can
522 prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National
523 Academy of Sciences of the United States of America* 111(2): 746-751

524 Catry FX, Moreira F, Cardillo E, Pausas JG (2012) Post-fire management of cork oak
525 forests. In: Moreira F, Arianoutsou M, Corona P, De las Heras J, (eds.) Post-fire management
526 and restoration of European forests. *Managing Forest Ecosystems*, Vol. 24, 195–222.
527 Springer.

- 528 Cardil A, Molina DM, Ramirez J, Vega-García C (2013) Trends in adverse weather
529 patterns and large wildland fires in Aragón (NE Spain) from 1978 to 2010. *Natural Hazards*
530 *and Earth System Science* 13: 1393–1399
- 531 Cardil A, Salis M, Spano D, Delogu G, Molina DM (2014) Large wildland fires and
532 extreme temperatures in Sardinia (Italy). *iForest - Biogeosciences and Forestry* 7: 162–169
- 533 Chas-Amil ML, Touza J, García-Martínez E (2013) Forest fires in the wildland–urban
534 interface: a spatial analysis of forest fragmentation and human impacts. *Applied Geography*
535 43: 127–137
- 536 Chessa PA, Delitala A (1997) Il clima della Sardegna. In ‘Collana Note Tecniche di
537 Agrometeorologia per la Sardegna’. (Ed. A Milella) pp. 17–38. (Chiarella: Sassari)
- 538 Chung W (2015) Optimizing Fuel Treatments to Reduce Wildland Fire Risk. *Current*
539 *Forestry Reports* 1: 44–51
- 540 Corona P, Ascoli D, Barbati A, Bovio G, Colangelo G, Elia M, Garfi V, IOvino F,
541 Laforteza R, Leone V, Lovreglio R, Marchetti M, Marchi E, Menguzzato G, Nocentini S,
542 Picchio R, Portoghesi L, Puletti N, Sanesi G, Chianucci F (2015) Integrated forest
543 management to prevent wildfires under Mediterranean environments. *Annals of Silvicultural*
544 *Research* 39: 1-22
- 545 Costa Alcubierre P, Castellnou Ribau M, Larrañaga Otxoa de Egileor A, Miralles
546 Bover M, Kraus PD (2011) Prevention of Large Wildfires using the Fire Types Concept. 88
547 pp. ISBN: 978-84-694-1457-6
- 548 Curt T, Borgniet L, Bouillon C (2013) Wildfire frequency varies with the size and
549 shape of fuel types in southeastern France: Implications for environmental management.
550 *Journal of Environmental Management* 117: 150-161
- 551 Duguay B, Alloza JA, Röder A, Vallejo R, Pastor F (2007) Modeling the effects of
552 landscape fuel treatments on fire growth and behaviour in a Mediterranean landscape (eastern
553 Spain). *International Journal of Wildland Fire* 16: 619–632
- 554 Elia M, Laforteza R, Colangelo G, Sanesi G (2014) A streamlined approach for the
555 spatial allocation of fuel removals in wildland–urban interfaces. *Landscape Ecology* 29:
556 1771–1784
- 557 Fernandes PM, Botelho HS (2003) A review of prescribed burning effectiveness in fire
558 hazard reduction. *International Journal of Wildland Fire* 12: 117-128
- 559 Fernandes PM, Loureiro C, Guiomar N, Pezzatti GB, Manso FT, Lopes L (2014) The
560 dynamics and drivers of fuel and fire in the Portuguese public forest. *Journal of*
561 *Environmental Management* 146: 373-382
- 562 Finney MA (2001). Design of regular landscape fuel treatment patterns for modifying
563 fire growth and behavior. *Forest Science* 47(2): 219–228
- 564 Finney MA (2002) Fire growth using minimum travel time methods. *Canadian Journal*
565 *of Forest Research* 32: 1420–1424
- 566 Finney MA (2005) The challenge of quantitative risk analysis for wildland fire. *Forest*
567 *Ecology and Management* 211: 97-108
- 568 Finney MA (2006) An overview of FlamMap fire modeling capabilities. In: Andrews
569 PL, Butler BW, comps. 2006. Fuels Management-How to Measure Success: Conference
570 Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO:

- 571 U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp.213–
572 220
- 573 Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK (2007) Simulation of
574 long-term landscape-level fuel treatment effects on large wildfires. *International Journal of*
575 *Wildland Fire* 16: 712–727
- 576 Ganteaume A, Jappiot M (2013) What causes large fires in Southern France. *Forest*
577 *Ecology and Management* 294: 76-85
- 578 Graham R, McCaffrey S, Jain T (2004) Science basis for changing forest structure to
579 modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research
580 Station, General Technical Report RMRS-GTR-120, 43 pp.
- 581 Hand MS, Gebert KM, Liang J, Calkin DE, Thompson MP, Zhou M (2014) Economics
582 of Wildfire Management - The Development and Application of Suppression Expenditure
583 Models. ISBN: 978-1-4939-0578-2 (online)
- 584 INFC (2005) Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio.
585 Ministero delle Politiche Agricole Alimentari e Forestali, Ispettorato Generale—Corpo
586 applicaForestale dello Stato. CRA—Istituto Sperimentale per l’Assesamento Forestale e per
587 l’Alpicoltura
- 588 Keane KE, Agee JK, Fule P, Keeley JE, Key C, Kitchen SG, Miller R, Schulte LA
589 (2008) Ecological effects of large fires on US landscapes: benefit or catastrophe?
590 *International Journal of Wildland Fire* 17, 696–712
- 591 Koutsias N, Martínez-Fernandez J, Allgower B (2010) Do factors causing wildfires
592 vary in space? Evidence from geographically weighted regression. *GIScience and Remote*
593 *Sensing* 47: 221–240
- 594 Koutsias N, Xanthopoulos G, Founda D, Xystrakis F, Nioti F, Pleniou M, Mallinis G
595 (2012) On the relationships between forest fires and weather conditions in Greece from long-
596 term 20 national observations (1894–2010). *International Journal of Wildland Fire* 22(4):
597 493-507
- 598 Lampin-Maillet C, Jappiot M, Long M, Bouillon C, Morge D, Ferrier JP (2010)
599 Mapping wildland-urban interfaces at large scales integrating housing density and vegetation
600 aggregation for fire prevention in the South of France. *Journal of Environmental*
601 *Management* 91: 732–741
- 602 Leone V, Signorile A (1997) Viali parafuoco: tipologie ed efficacia. *L’Italia Forestale*
603 *e Montana* 5: 307-328
- 604 Lovreglio R, Marciano A, Patrone A, Leone V (2012) Forest fire motives in Italy:
605 preliminary results of a pilot survey in the most fire-affected Provinces. *iForest -*
606 *Biogeosciences and Forestry* 9(4): 137–147
- 607 Liu Z, Yang J, He HS (2013) Studying the effects of fuel treatment based on burn
608 probability on a boreal forest landscape. *Journal of Environmental Management* 115: 42-52
- 609 Luciano P, Roversi PF (2001) Fillofagi delle querce in Italia. 161 pp. Industria Grafica
610 Poddighe s.r.l, Sassari.
- 611 Martínez J, Vega-Garcia C, Chuvieco E (2009). Human-caused wildfire risk rating for
612 prevention planning in Spain. *Journal of Environmental Management* 90: 1241–1252

- 613 Mazzoleni S, di Pasquale G, Mulligan M, di Martino P, Rego F (2004) Recent
614 dynamics of the Mediterranean vegetation and landscape. 320 pp. ISBN 0-470-09369-2
- 615 Meddour-Sahar O, Meddour R, Leone V, Lovreglio R, Derridj A (2013) Analysis of
616 forest fires causes and their motivations in northern Algeria: the Delphi method. *iForest -*
617 *Biogeosciences and Forestry* 6: 247-254
- 618 Mercer DE, Haigh RG, Prestemon JP (2008) Analyzing trade-offs between fuels
619 management, suppression, and damages from wildfire. In: “The Economics of Forest
620 Disturbances: Management, Suppression, and Damages from Wildfire” (Holmes TP,
621 Prestemon JP, Abt KL eds). Series “Forestry Sciences”, vol. 79, Springer, The Netherlands,
622 pp. 247-272
- 623 Miller C, Ager AA (2013) A review of recent advances in risk analysis for wildfire
624 management. *International Journal of Wildland Fire* 22: 1–14
- 625 Miller C, Parisien MA, Ager AA, Finney MA (2008) Evaluating spatially-explicit burn
626 probabilities for strategic fire management planning. In ‘Modelling, monitoring and
627 management of forest fires’. (Eds J De las Heras, CA Brebbia, D Viegas, V Leone) pp. 245–
628 252 (WIT Press: Boston, MA).
- 629 Moghaddas JJ, Collins BM, Menning K, Moghaddas EEY, Stephens SL (2010) Fuel
630 treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada.
631 *Canadian Journal of Forest Research* 40: 1751–1765
- 632 Molina JR, Rodriguez y Silva F, Herrera MA (2011) Potential crown fire behaviour in
633 *Pinus pinea* stands following different fuel treatments. *Forest Systems* 20: 266-277
- 634 Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot E, Barbati A,
635 Corona P, Vaz P, Xanthopoulos G, Mouillot F, Bilgili E (2011) Landscape–wildfire
636 interactions in southern Europe: implications for landscape management. *Journal of*
637 *Environmental Management* 92(10): 2389–2402
- 638 Moritz MM, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J,
639 McCaffrey S, Odion DC, Schoennagel T, Syphard AD (2014). Learning to coexist with
640 wildfire. *Nature* 515: 58-66
- 641 Oliveira S, Oehler F, San-Miguel-Ayanz J, Camia A, Pereira JMC (2012) Modeling
642 spatial patterns of fire occurrence in Mediterranean Europe using multiple regression and
643 random forest. *Forest Ecology and Management* 275: 117-129
- 644 Palahi M, Mavsar R, Gracia C, Birot Y (2008) Mediterranean forests under focus.
645 *International Forestry Review* 10(4): 676–688
- 646 Parisien M, Junor DR, Kafka VG (2007) Comparing landscape-based decision rules of
647 placement of fuel treatments in the boreal mixed-wood of western Canada. *International*
648 *Journal of Wildland Fire* 16: 664–672
- 649 Pausas, JG (1997) Resprouting of *Quercus suber* in NE Spain after fire. *Journal of*
650 *Vegetation Science* 8: 703-706.
- 651 Pausas JG (2004) Changes in fire and climate in the eastern Iberian peninsula
652 (Mediterranean Basin). *Climatic Change* 63: 337–350
- 653 Pausas JG, Fernandez-Munoz S (2012) Fire regime changes in the Western
654 Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change* 110:
655 215–226

- 656 Pellizzaro G, Duce P, Ventura A, Zara P (2007) Seasonal variations of live moisture
657 content and ignitability in shrubs of the Mediterranean Basin. *International Journal of*
658 *Wildland Fire* 16: 633–641
- 659 Pellizzaro G, Ventura A, Zara P (2005) Influence of seasonal weather variations on fuel
660 status for some shrubs typical of Mediterranean Basin. In: Proceedings 6th fire and forest
661 meteorology symposium and ‘19th Interior West Fire Council Meeting’. 24–27 October
662 2005, Canmore, AB, Canada. P1.16. (CD-ROM) (American Meteorological Society: Boston,
663 MA)
- 664 Pellizzaro G, Arca B, Pintus GV, Ferrara R, Duce P (2012) Wildland-urban interface
665 dynamics during the last 50 years in North East Sardinia. In: Spano D, Bacciu V, Salis M,
666 Sirca C (eds) *Modelling Fire Behavior and Risk*. pp 249–254. Nuova Stampa Color Publisher
- 667 Pinol JK, Beven J, Viegas DX (2005) Modelling the effect of fire exclusion and
668 prescribed fire on wildfire size in Mediterranean ecosystems. *Ecological Modelling* 183,
669 397–409
- 670 Prestemon JP, Abt K, Gebert K (2008) Suppression cost forecast in advance of wildfire
671 seasons. *Forest Science* 54(4): 381–396
- 672 Reinhardt ED, Keane R, Calkin DE, Cohen JD (2008). Objectives and considerations
673 for wildland fuel treatment in forested ecosystems of the interior western United States.
674 *Forest Ecology and Management* 256: 1997–2006
- 675 Richards GD (1990) An elliptical growth model of forest fire fronts and its numerical
676 solution. *International Journal for Numerical Methods in Engineering* 30: 1163–1179
- 677 Rothermel RC (1972) A mathematical model for predicting fire spread in wildland
678 fuels. USDA forest service research paper, INT-115. Intermountain Forest and Range
679 Experiment Station, Ogden, UT
- 680 Ruiz-Mirazo J, Martinez Fernandez J, Vega-Garcia C (2012) Pastoral wildfires in the
681 Mediterranean: understanding their linkages to land cover patterns in managed landscapes.
682 *Journal of Environmental Management* 98: 43–50
- 683 Safford HD, Schmidt DA, Carlson CH (2009) Effects of fuel treatments on fire severity
684 in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. *Forest*
685 *Ecology and Management* 258: 773–787
- 686 Salis M, Ager AA, Alcasena F, Arca B, Finney MA, Pellizzaro G, Spano D (2015)
687 Analyzing seasonal patterns of wildfire likelihood and intensity in Sardinia, Italy.
688 *Environmental Monitoring and Assessment* 187: 4175
- 689 Salis M, Ager AA, Arca B, Finney MA, Bacciu V, Duce P, Spano D (2013) Assessing
690 exposure of human and ecological values to wildfire in Sardinia, Italy. *International Journal*
691 *of Wildland Fire* 22(4): 549–565
- 692 Salis M, Ager AA, Finney MA, Arca B, Spano D (2014) Analyzing spatiotemporal
693 changes in wildfire regime and exposure across a Mediterranean fire-prone area. *Natural*
694 *Hazards* 71(3): 1389–1418
- 695 San-Miguel-Ayanz J, Moreno JM, Camia A (2013) Analysis of large fires in European
696 Mediterranean landscapes: lessons learned and perspectives. *Forest Ecology and*
697 *Management* 294: 11–22

- 698 Sardinia Regional Government (2014a) Piano Regionale Antincendio 2014-2016,
699 Revisione 2014.
700 <http://www.sardegnaambiente.it/index.php?xsl=612&s=256124&v=2&c=4594&idsito=20>
- 701 Sardinia Regional Government (2014b) Prescrizioni Regionali Antincendio 2014-2016.
702 28 pp. http://www.sardegnaambiente.it/documenti/20_467_20141007092620.pdf
- 703 Sardinia Regional Government (2014c) Programma Regionale di Sviluppo 2014-2019.
704 193 pp. http://www.regione.sardegna.it/documenti/1_73_20141024103003.pdf
- 705 Schaaf MD, Wiitala MA, Schreuder MD, Weise DR (2004) An evaluation of the
706 economic tradeoffs of fuel treatment and fire suppression on the Angeles National Forest
707 using the Fire Effects Tradeoff Model (FETM). In Proceedings of the II International
708 Symposium on Fire Economics, Policy and Planning: A Global Vision, April 19–22, 2004,
709 Córdoba, Spain.
- 710 Schmidt DA, Taylor AH, Skinner CN (2008) The influence of fuels treatment and
711 landscape arrangement on simulated fire behavior, Southern Cascade range, California.
712 *Forest Ecology and Management* 255: 3170–3184
- 713 Schmuck G, San-Miguel-Ayanz J, Camia A, Durrant T, Boca R, Libertà G, Petroliaqkis
714 T, Di Leo M, Rodrigues D, Boccacci F, Schulte E (2014) Forest Fires in Europe Middle East
715 and North Africa 2013. 107 pp. ISBN 978-92-79-39627-4
716 http://forest.jrc.ec.europa.eu/media/cms_page_media/9/FireReport2013_final2pdf_2.pdf
- 717 Scott JH (2006) An analytical framework for quantifying wildland fire risk and fuel
718 treatment benefit. In: Andrews PL, Butler BW, comps. 2006. Fuels Management-How to
719 Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings
720 RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky
721 Mountain Research Station. p. 169–184
- 722 Scott JH, Burgan R (2005) Standard fire behavior fuel models: a comprehensive set for
723 use with Rothermel's Surface Fire Spread Model. USDA Forest Service, Rocky Mountain
724 Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO)
- 725 Scott JH, Thompson MP, Calkin DE (2013) A Wildfire Risk Assessment Framework
726 for Land and Resource Management. Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of
727 Agriculture, Forest Service, Rocky Mountain Research Station, 83 pp.
- 728 Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR,
729 Kennedy PL, Schwilk DW (2012) Effects of forest fuel reduction treatments in the United
730 States. *BioScience* 62: 549–560
- 731 Stephens SL, Ruth LW (2005) Federal forest fire policy in the United States.
732 *Ecological Applications* 15: 532-542
- 733 Thompson MP, Calkin DE (2011) Uncertainty and risk in wildland fire management: a
734 review. *Journal of Environmental Management* 92, 1895–1909
- 735 Thompson MP, Valliant NM, Haas JR, Gebert KM, Stockmann KD (2013) Quantifying
736 the potential impacts of fuel treatments on wildfire suppression costs. *Journal of Forestry*
737 111: 49–58
- 738 Trigo RM, Pereira JM, Mota B, Calado T, Dacamara C, Santo F (2006). Atmospheric
739 conditions associated with the exceptional fire season of 2003 in Portugal. *International*
740 *Journal of Climatology* 26: 1741-1757

741 Valor T, González-Olabarria JR, Piqué M (2015) Assessing the impact of prescribed
742 burning on the growth of European pines. *Forest Ecology and Management* 343: 101-109

743 Viegas DX, Simeoni A, Xanthopoulos G, Rossa C, Ribeiro LM, Pita LP, Stipanicev D,
744 Zinoviev A, Weber R, Dold J, Caballero D, San-Miguel-Ayanz J (2009) Recent forest fire
745 related accidents in Europe. European Commission Joint Research Centre Institute for
746 Environment and Sustainability, Luxembourg

747 Vogler KC, Ager AA, Day MA, Jennings M, Bailey JD (2015) Prioritization of Forest
748 Restoration Projects: Tradeoffs between Wildfire Protection, Ecological Restoration and
749 Economic Objectives. *Forests* 6: 4403-4420

750 Wei Y, Rideout D, Kirsch A (2008) An optimization model for locating fuel treatments
751 across a landscape to reduce expected fire losses. *Canadian Journal of Forest Research* 38:
752 868-877

753 Xanthopoulos G, Caballero D, Galante M, Alexandrian D, Rigolot E, Marzano R
754 (2006) Forest Fuels Management in Europe. In: Andrews PL, Butler BW, comps. 2006. Fuels
755 Management-How to Measure Success: Conference Proceedings. 28-30 March 2006;
756 Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture,
757 Forest Service, Rocky Mountain Research Station. p. 29-46

758 Wu Z, He H, Liu Z, Liang Y (2013) Comparing fuel reduction treatments for reducing
759 wildfire size and intensity in a boreal forest landscape of northeastern China. *Science of the*
760 *Total Environment* 454-455: 30-39

761 Zagas T, Raptis D, Zagas D, Karamanolis D (2013) Planning and assessing the
762 effectiveness of traditional silvicultural treatments for mitigating wildfire hazard in pine
763 woodlands of Greece. *Natural Hazards* 65: 545-561

764 www.centrometeo.com

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

766 www.sardegnameoportale.it

767 www.tutiempo.es

768 www.wunderground.com

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	CH	CBD	CBH
	(t ha ⁻¹)	(t ha ⁻¹)	(cm)				(m)	(100* kg m ⁻³)	(m)
FM25	1.2	0.0	20	Grasslands	below 900 m	Untreated	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			0	0	0
FM29	5.3	4.1	45	Garrigue			0	0	0
FM30	15.0	12.5	135	Mediterranean Maquis			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	above 900 m	Untreated	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			0	0	0
FM49	6.4	4.9	70	Garrigue			0	0	0
FM50	18.0	15.0	160	Mediterranean Maquis			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	below 900 m	Treated	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			0	0	0
FM69	2.5	3.5	45	Garrigue			0	0	0
FM70	4.5	11.0	135	Mediterranean Maquis			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	above 900 m	Treated	0	0	0
FM86	1.2	0.0	30	Mix Agricultural Areas			0	0	0
FM87	1.0	2.0	80	Orchards			10	10	2
FM88	1.2	0.0	35	Herbaceous Pastures			0	0	0
FM89	2.5	3.5	70	Garrigue			0	0	0

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

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

FUEL TREATMENT STRATEGY	BP	CFL (m)	FS (ha)	FPI
<i>NO-TREAT</i>	7.71E-03a (8.28E-03)	1.125ab (0.825)	564.88a (472.09)	531.43a (564.44)
<i>RAND-3%</i>	7.61E-03b (8.29E-03)	1.097cd (0.823)	559.82b (475.51)	526.53a (568.80)
<i>RAND-9%</i>	7.11E-03d (7.77E-03)	1.065e (0.818)	531.55d (464.42)	494.03c (539.37)
<i>RAND-15%</i>	6.84E-03e (7.61E-03)	1.034f (0.812)	501.56f (448.34)	472.22d (523.41)
<i>ROAD-3%</i>	7.06E-03d (7.57E-03)	1.124b (0.822)	540.04c (464.45)	488.61c (515.26)
<i>ROAD-9%</i>	6.35E-03g (6.86E-03)	1.091d (0.813)	501.66f (441.38)	435.26f (454.48)
<i>ROAD-15%</i>	6.08E-03i (6.74E-03)	1.065e (0.803)	472.05h (407.64)	410.49h (437.21)
<i>WUI-3%</i>	7.31E-03c (7.69E-03)	1.137a (0.830)	553.80b (471.38)	507.74b (534.19)
<i>WUI-9%</i>	6.66E-03f (7.11E-03)	1.104c (0.819)	513.35e (440.48)	455.31e (473.02)
<i>WUI-15%</i>	6.21E-03h (6.81E-03)	1.076e (0.807)	481.80g (416.96)	424.62g (444.03)
<i>Group comparison (Kruskal-Wallis test, p-value)</i>	0.001	0.001	0.001	0.001

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

9

Figure 1
[Click here to download high resolution image](#)

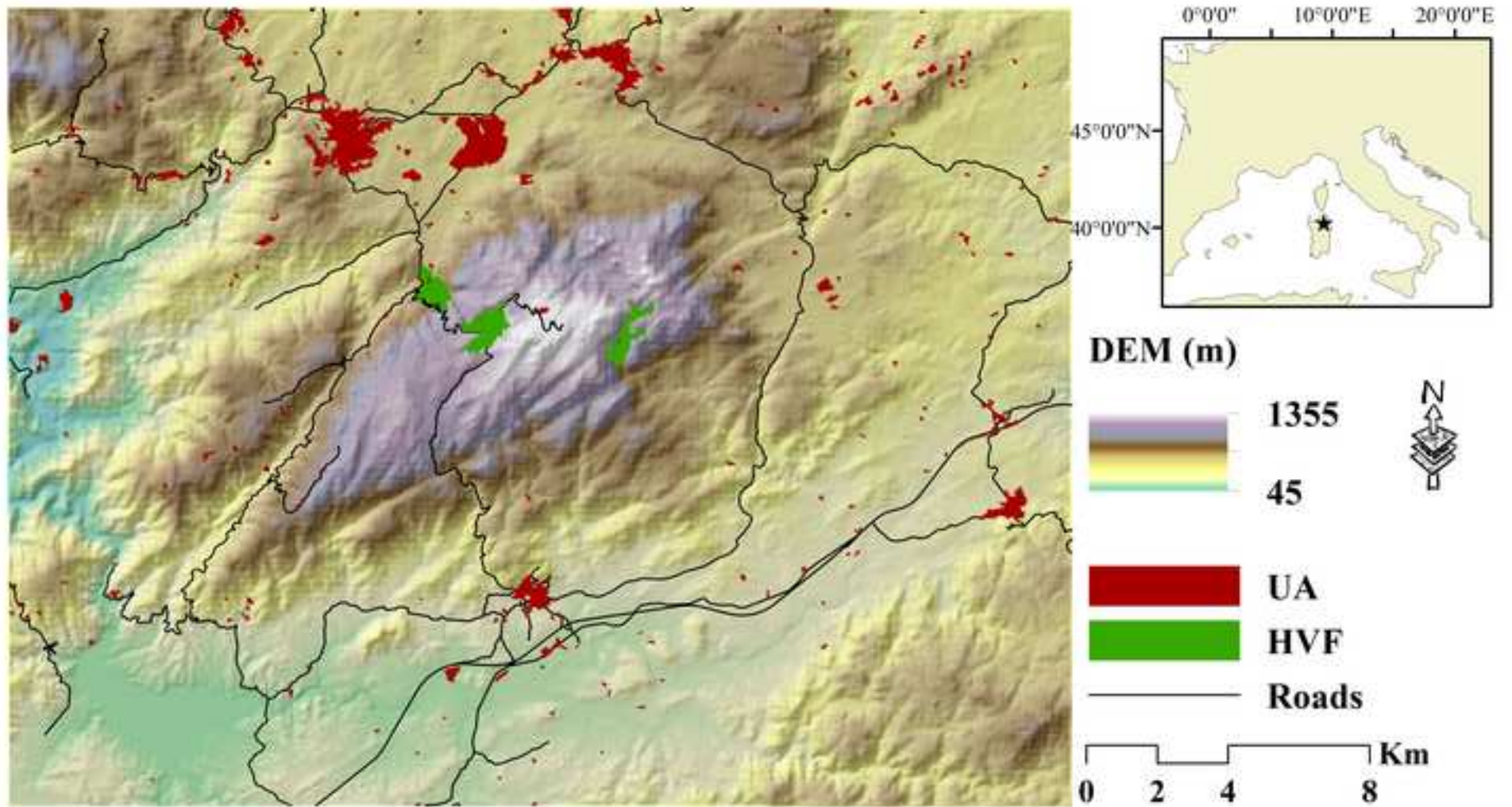


Figure 2
[Click here to download high resolution image](#)

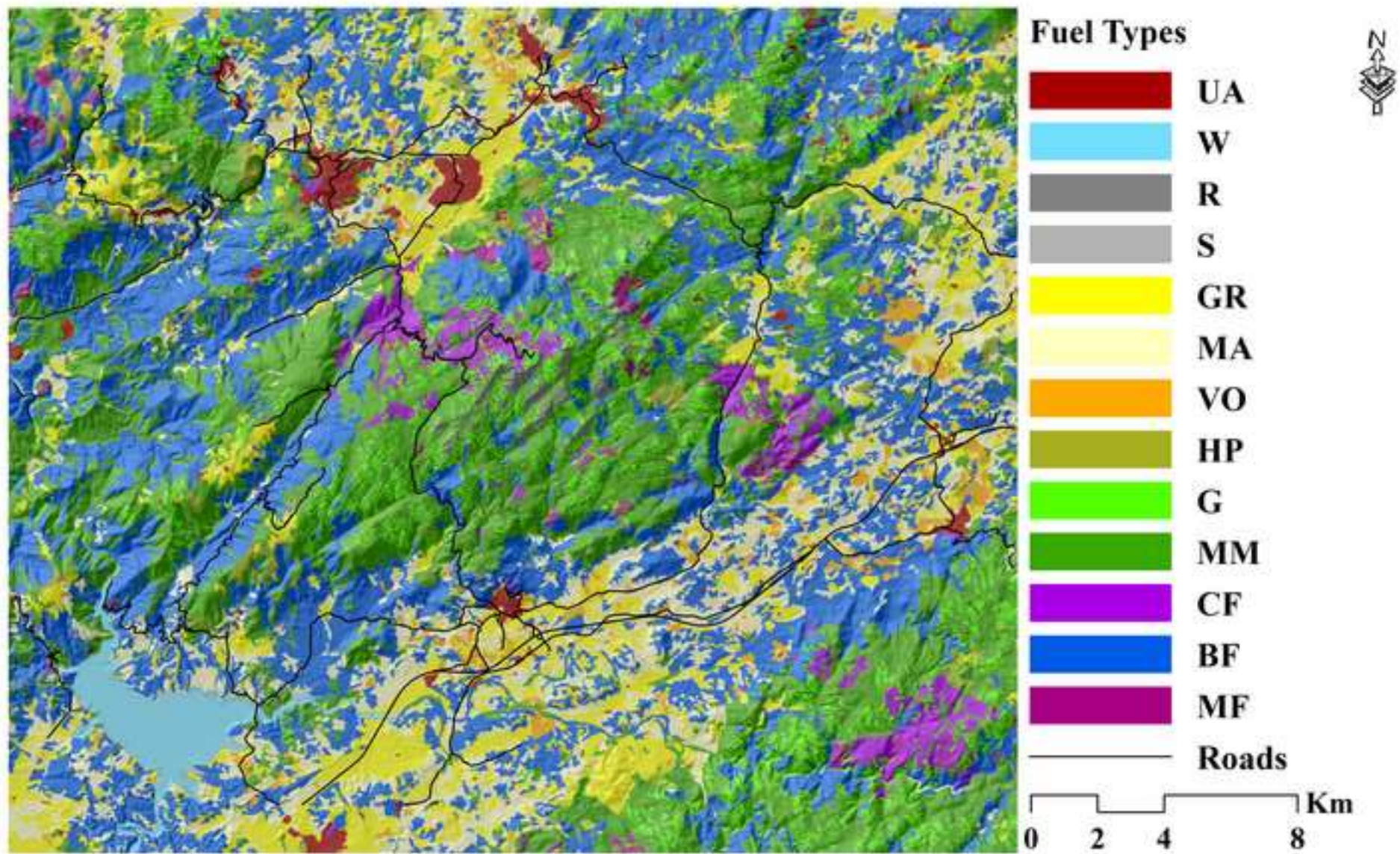


Figure 3

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	7				
275	19	7				
586	19	7				
178	20	7				
361	20	7				
14	21	7				
15	21	7				
227	21	7				
278	21	7				
545	21	7				
228	22	7				
229	23	7				
363	23	7				
450	23	7				
230	24	7				
231	24	7				
366	24	7				

Figure 4a
[Click here to download high resolution image](#)

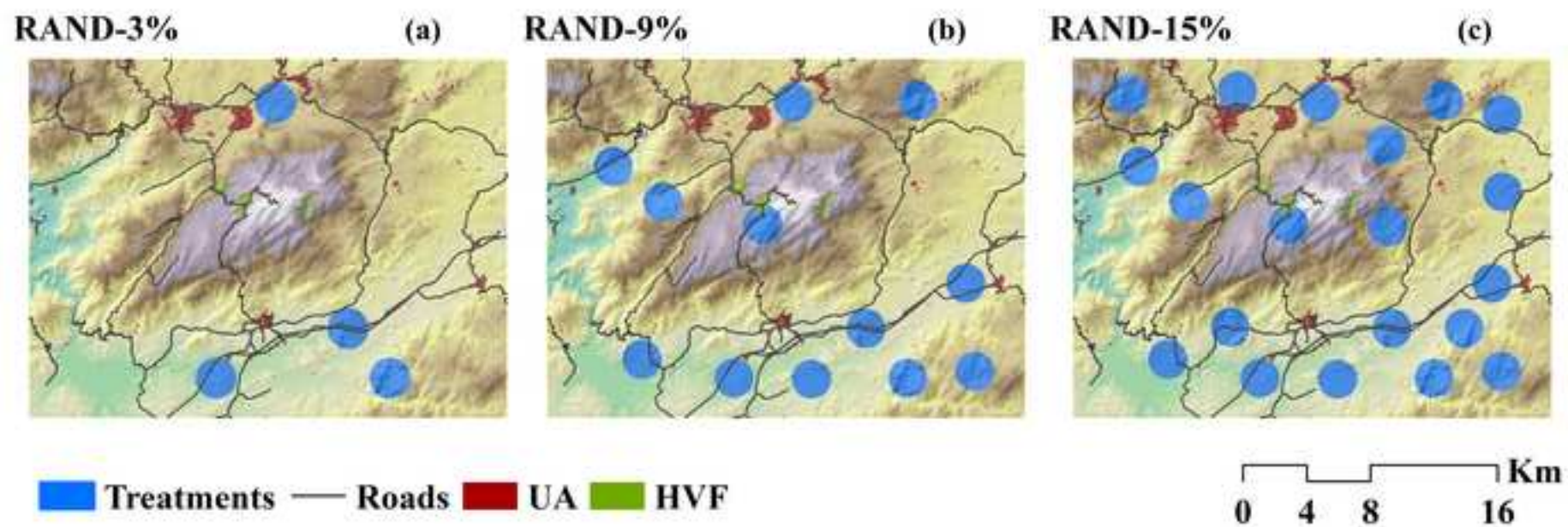
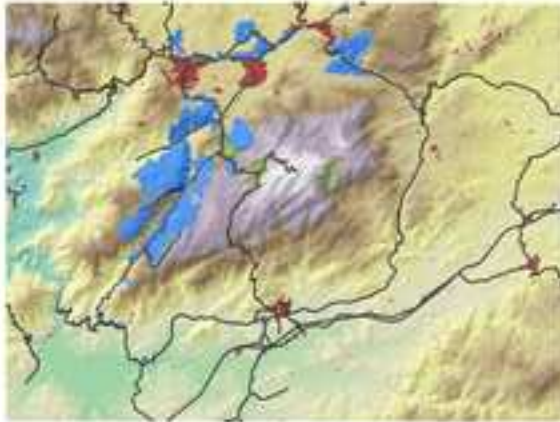


Figure 4b
[Click here to download high resolution image](#)

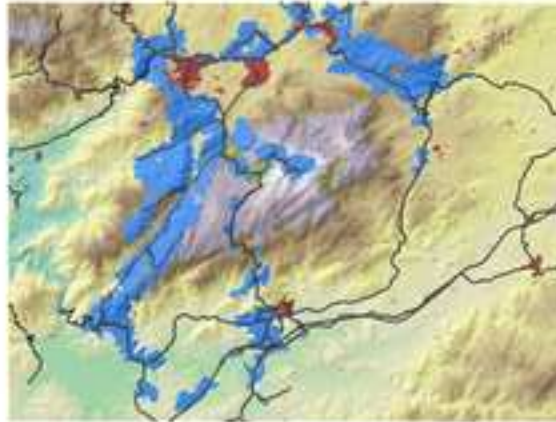
ROAD-3%

(d)



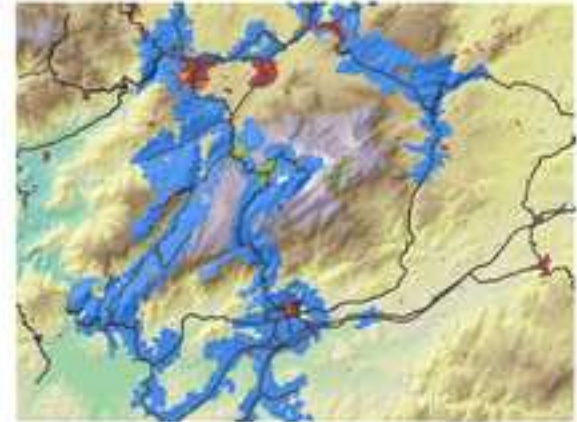
ROAD-9%

(e)



ROAD-15%

(f)



■ Treatments — Roads ■ UA ■ HVF

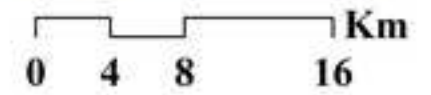


Figure 4c
[Click here to download high resolution image](#)

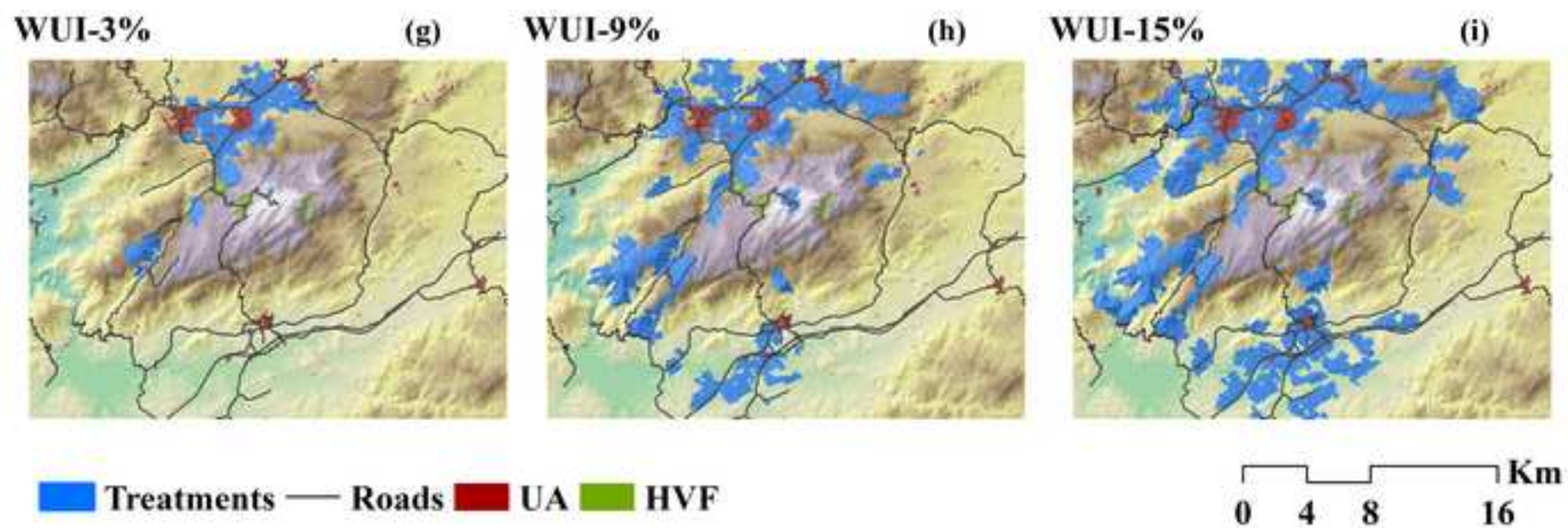


Figure 5

	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	
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	
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	
NO-TREAT	215.229				
RAND		213.244	200.08	191.251	FPI
ROAD		197.888	176.28	166.248	
WUI		205.634	184.401	171.972	
NO-TREAT	564.884				
RAND		559.824	531.554	501.558	FS
ROAD		540.041	501.655	472.05	
WUI		553.8	513.351	481.798	
NO-TREAT	531.43				
RAND		526.529	494.026	472.225	FPI
ROAD		488.613	435.259	410.489	
WUI		507.739	455.31	424.621	

Figure 6a
[Click here to download high resolution image](#)

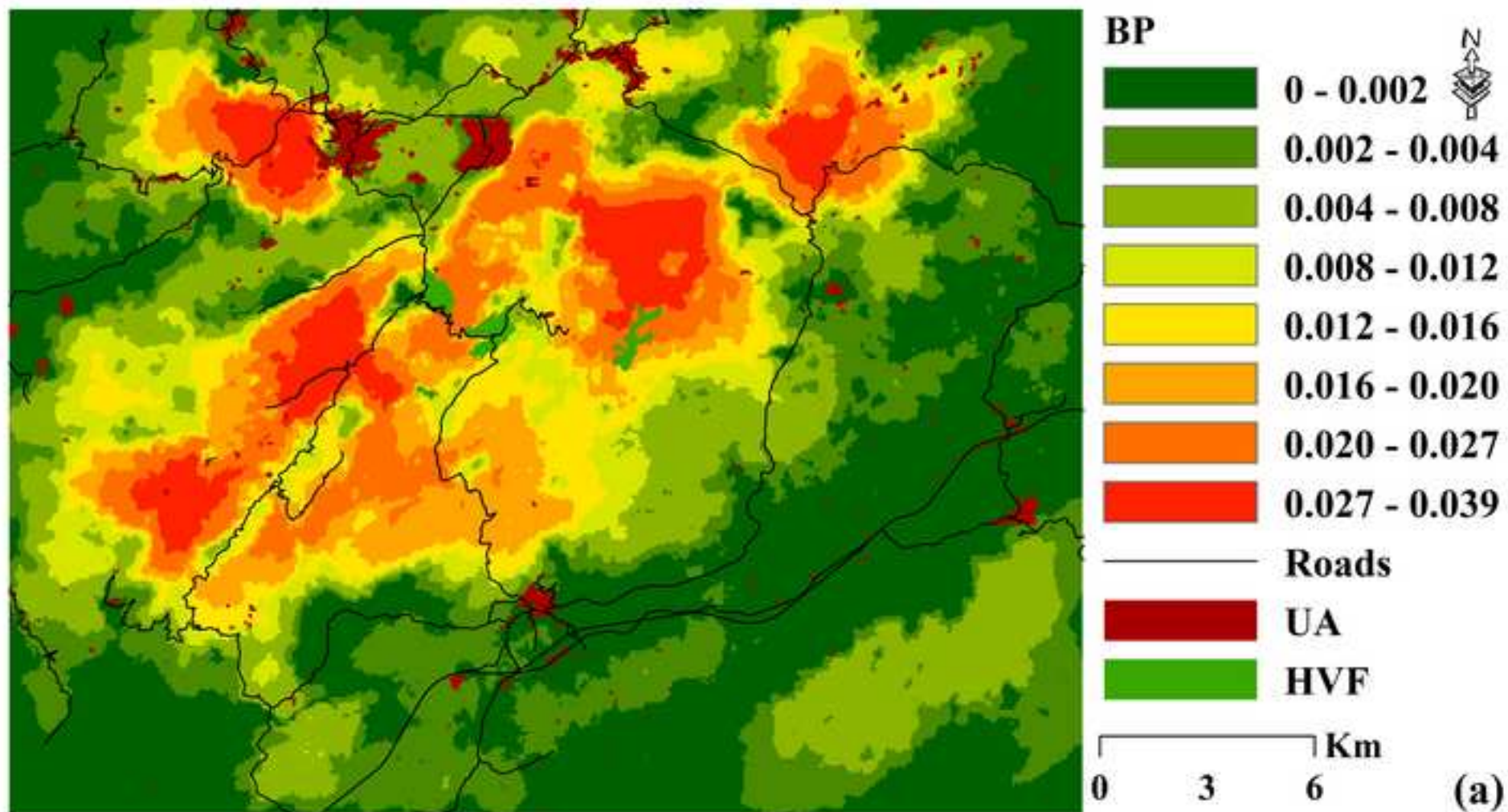


Figure 6b

[Click here to download high resolution image](#)

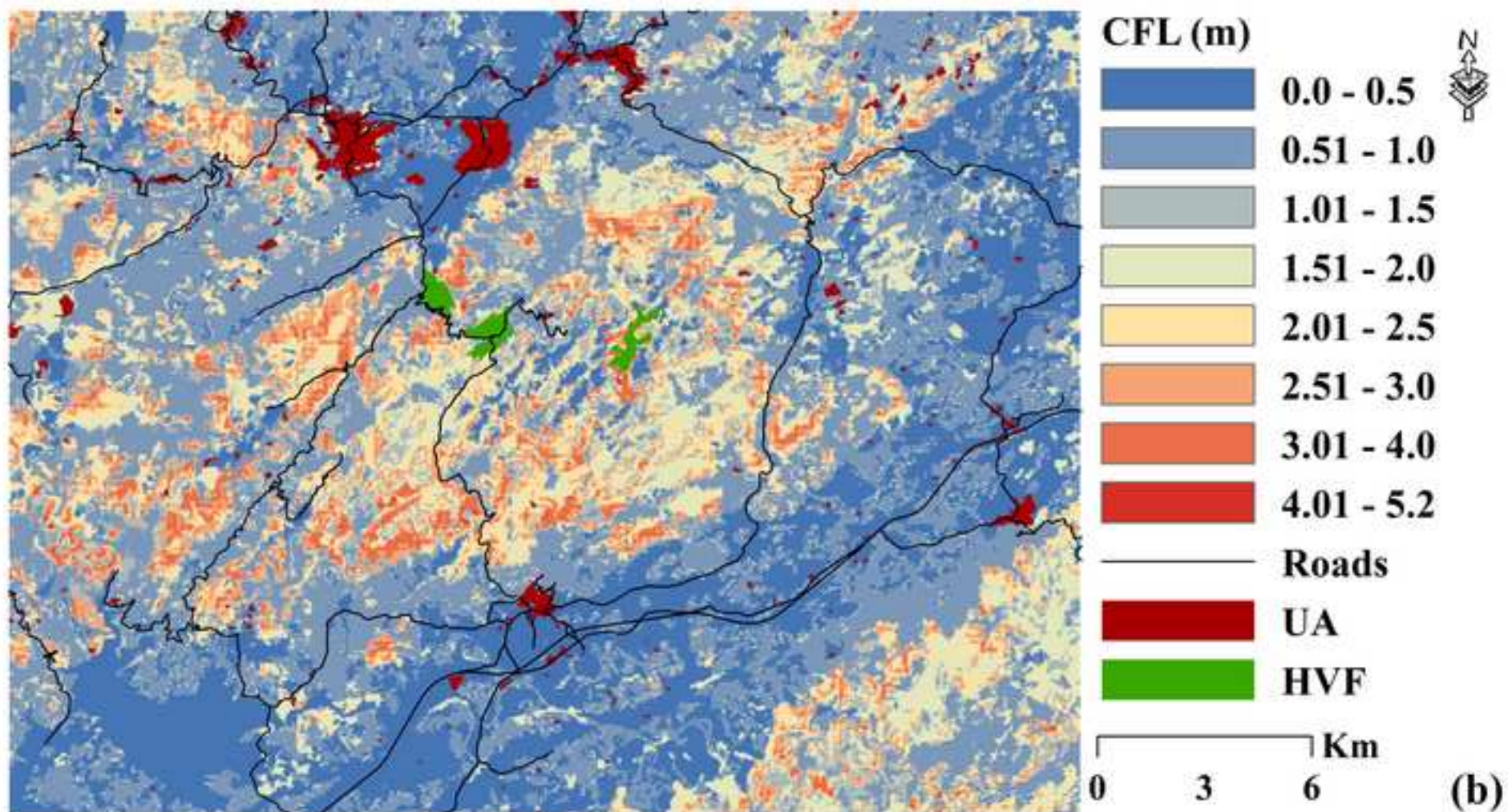


Figure 6c
[Click here to download high resolution image](#)

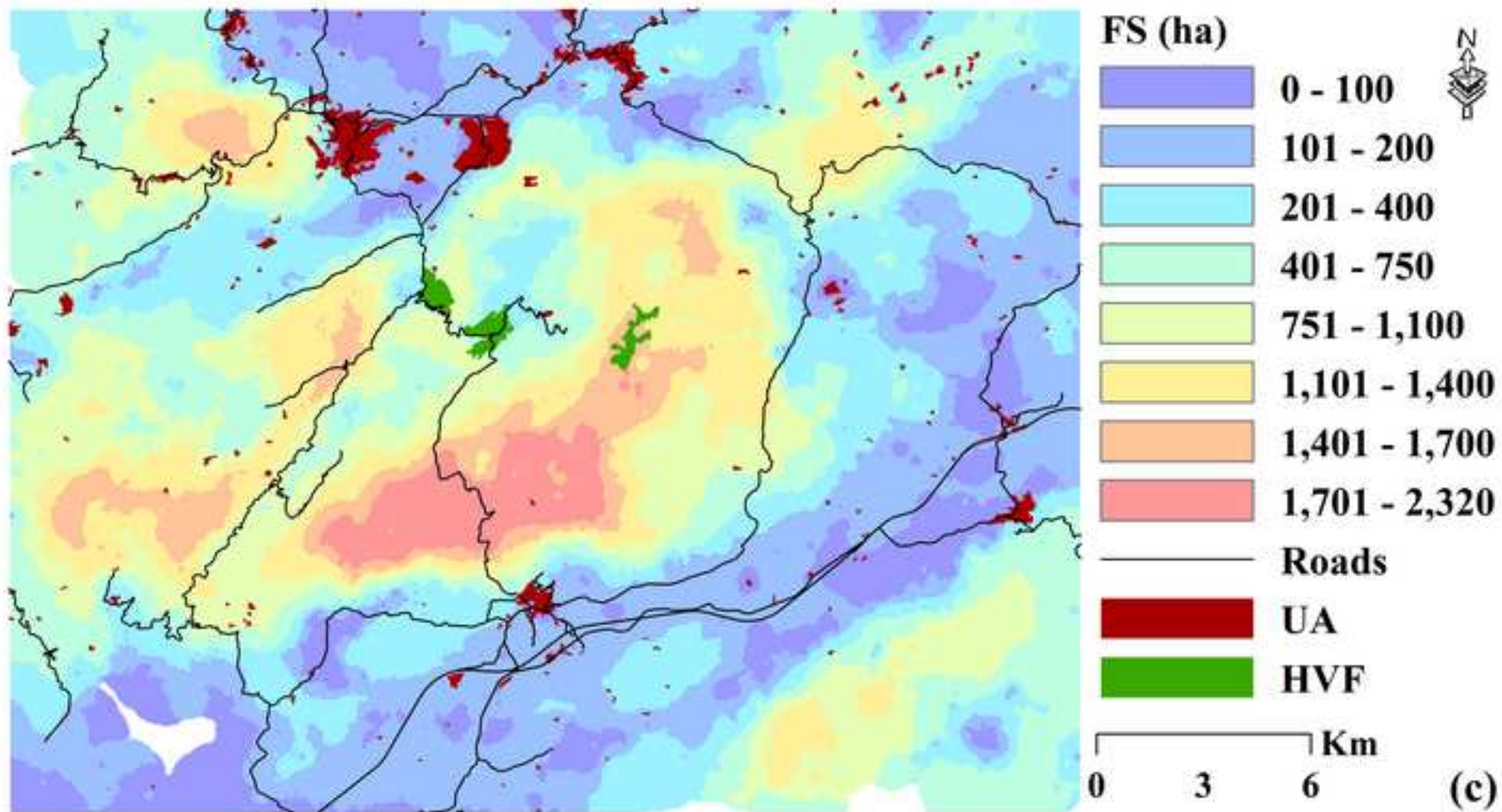


Figure 7a

[Click here to download high resolution image](#)

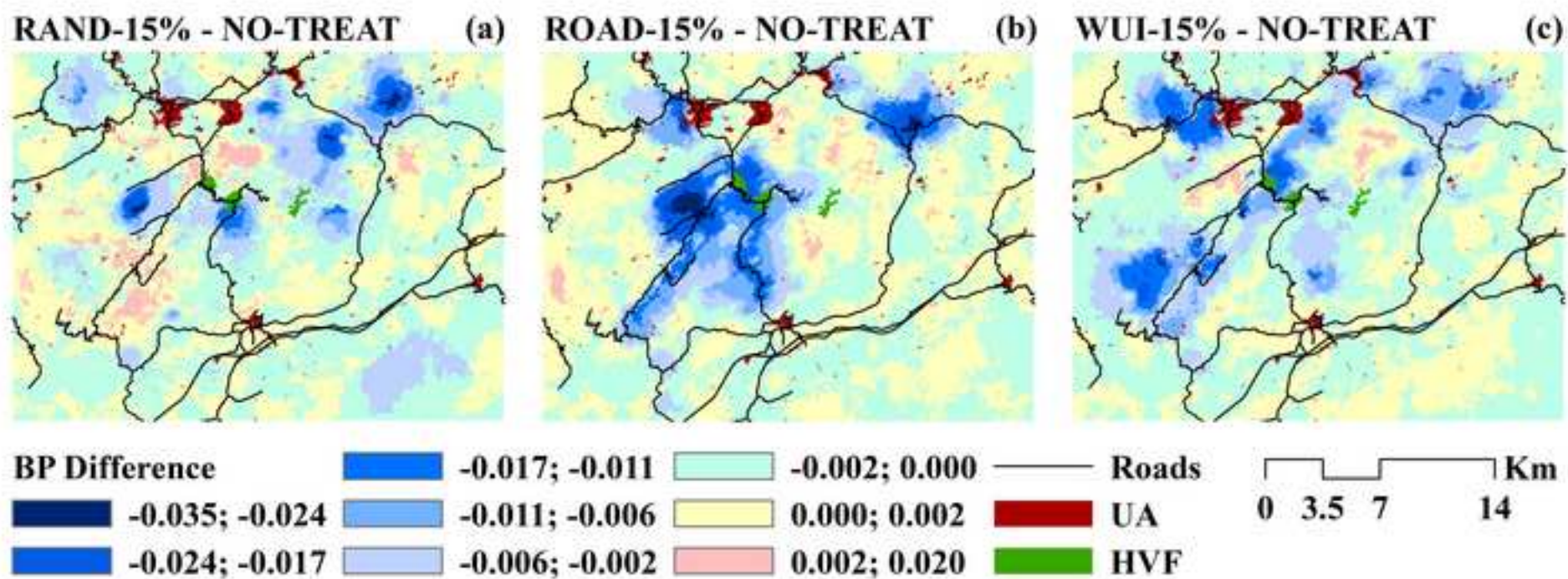


Figure 7b

[Click here to download high resolution image](#)

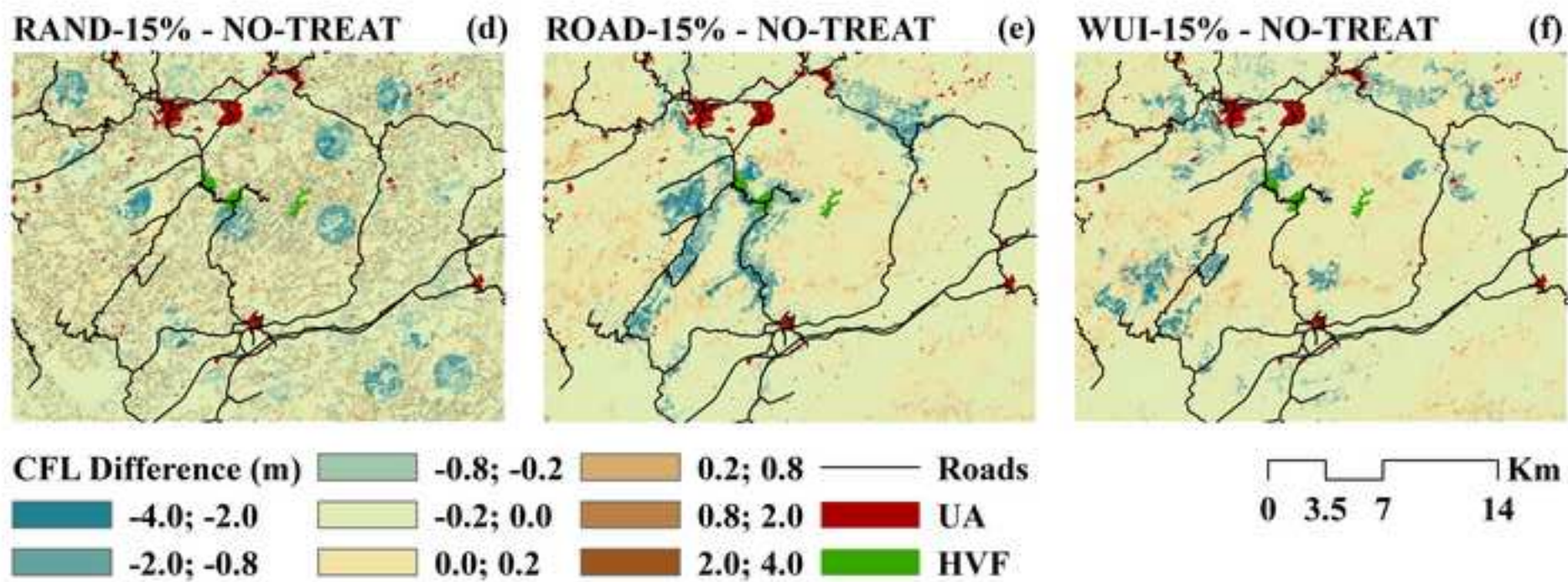


Figure 7c

[Click here to download high resolution image](#)

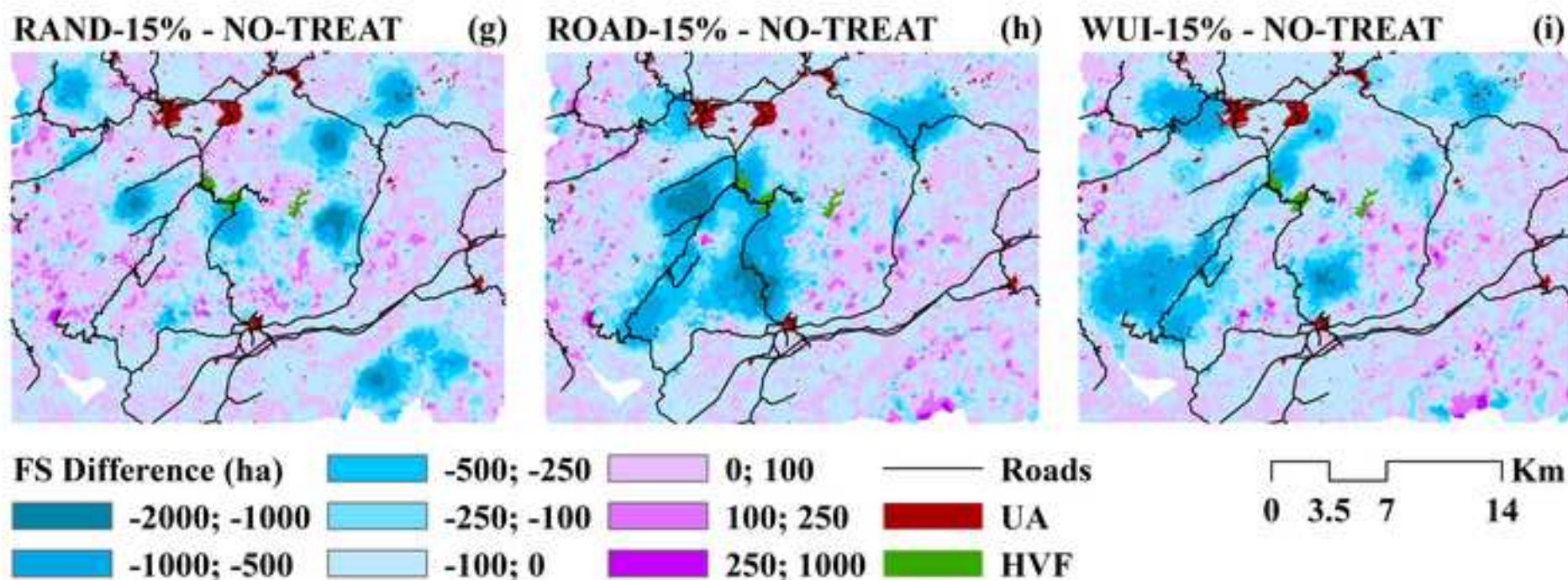


Figure 7d

[Click here to download high resolution image](#)

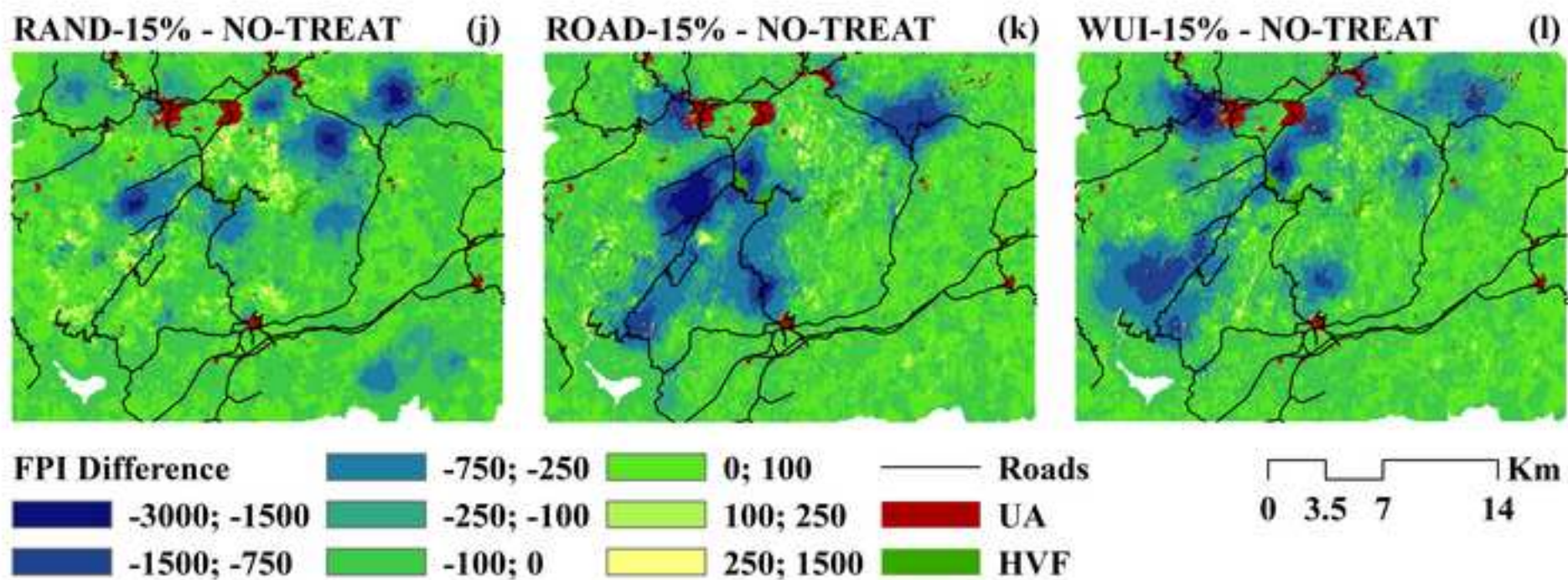


Figure 8a
[Click here to download high resolution image](#)

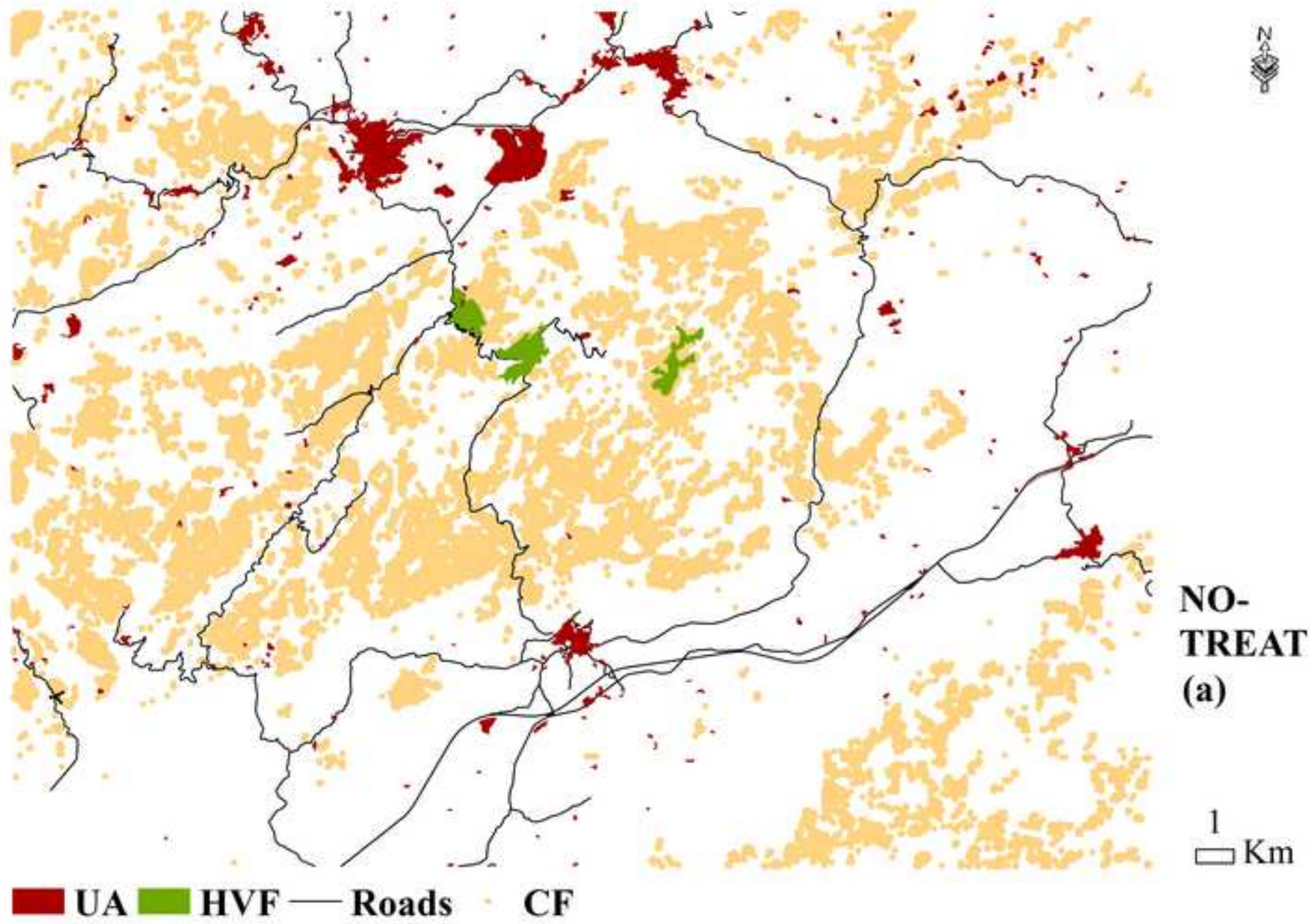


Figure 8b
[Click here to download high resolution image](#)

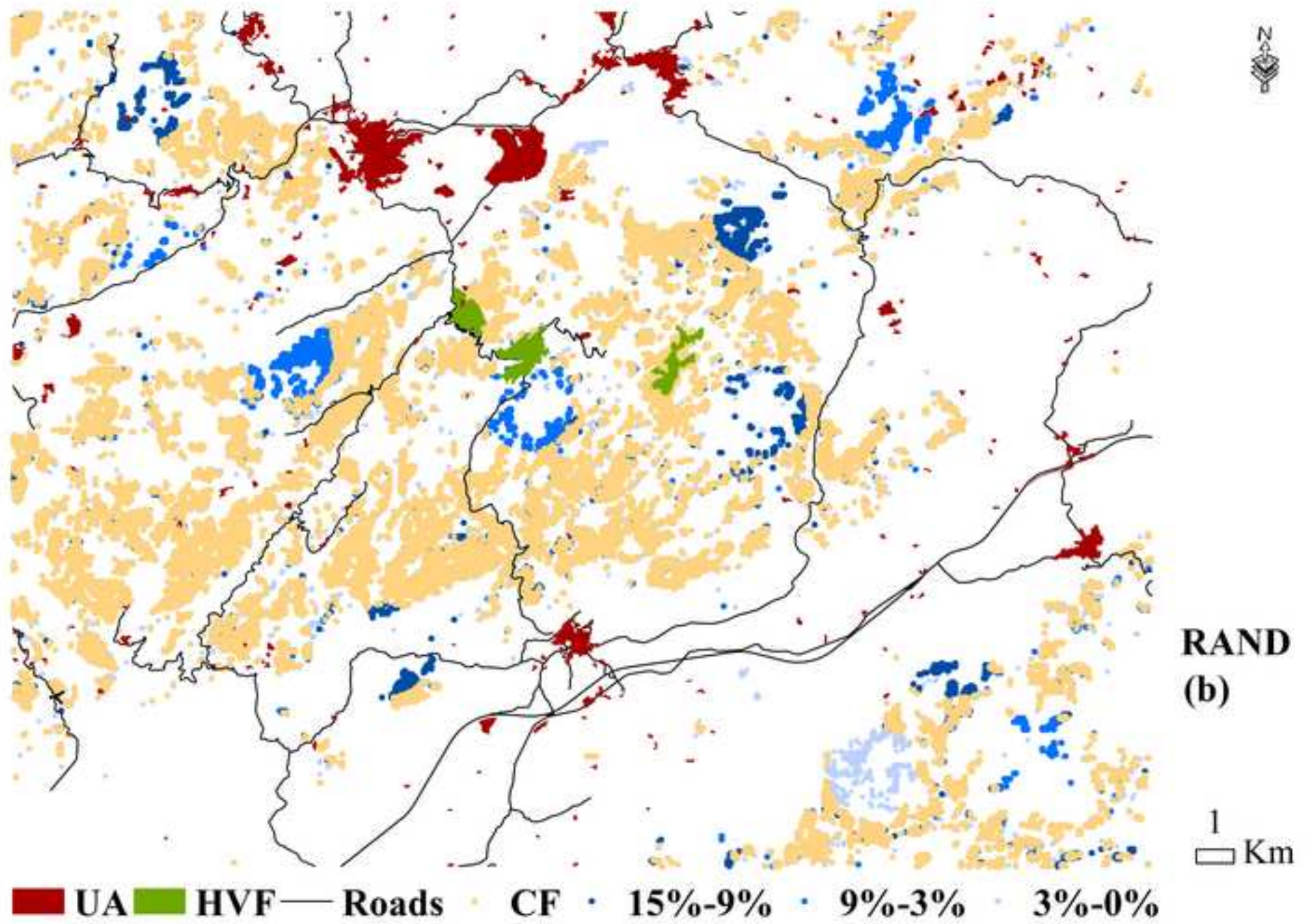


Figure 8c
[Click here to download high resolution image](#)

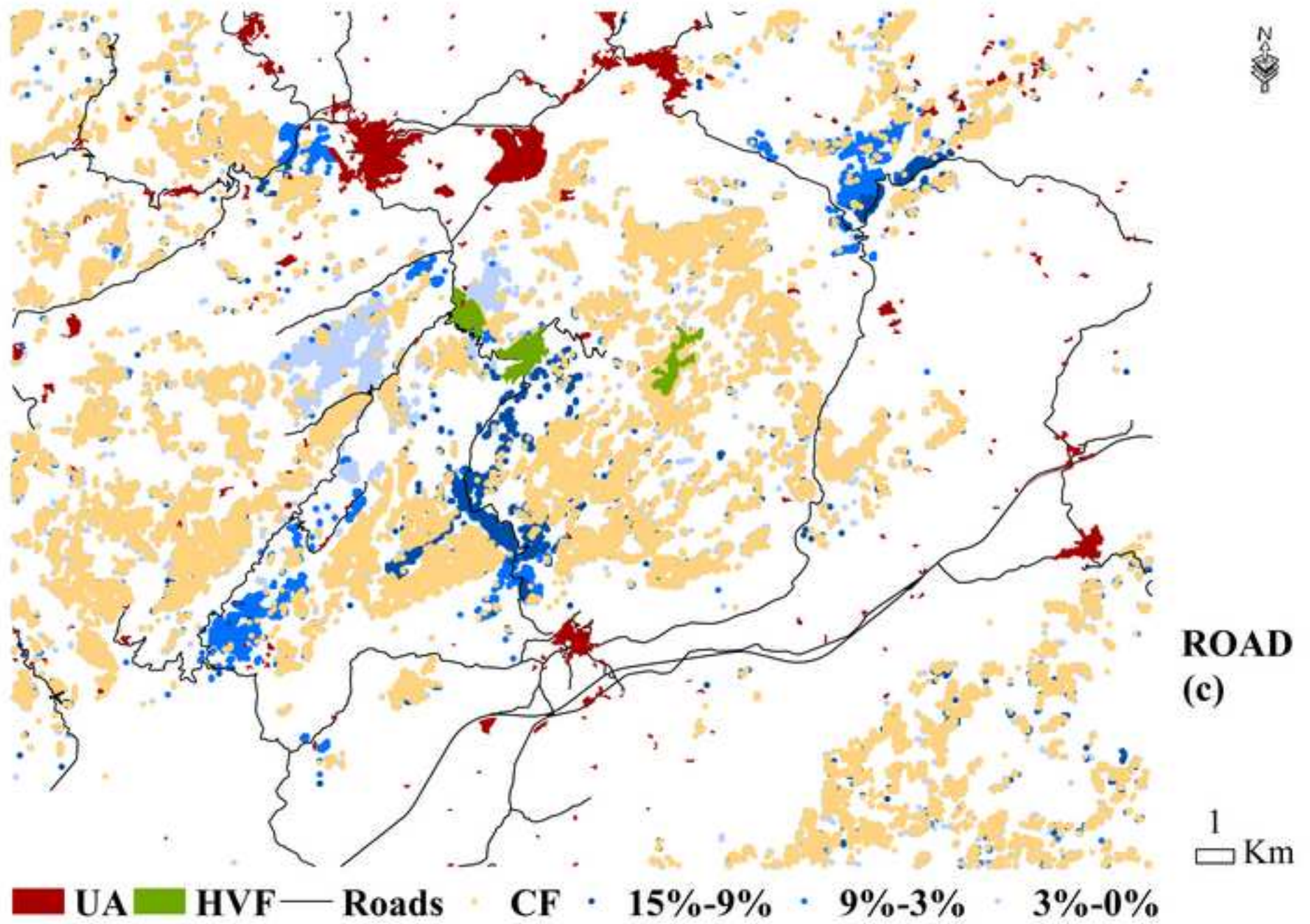


Figure 8d
[Click here to download high resolution image](#)

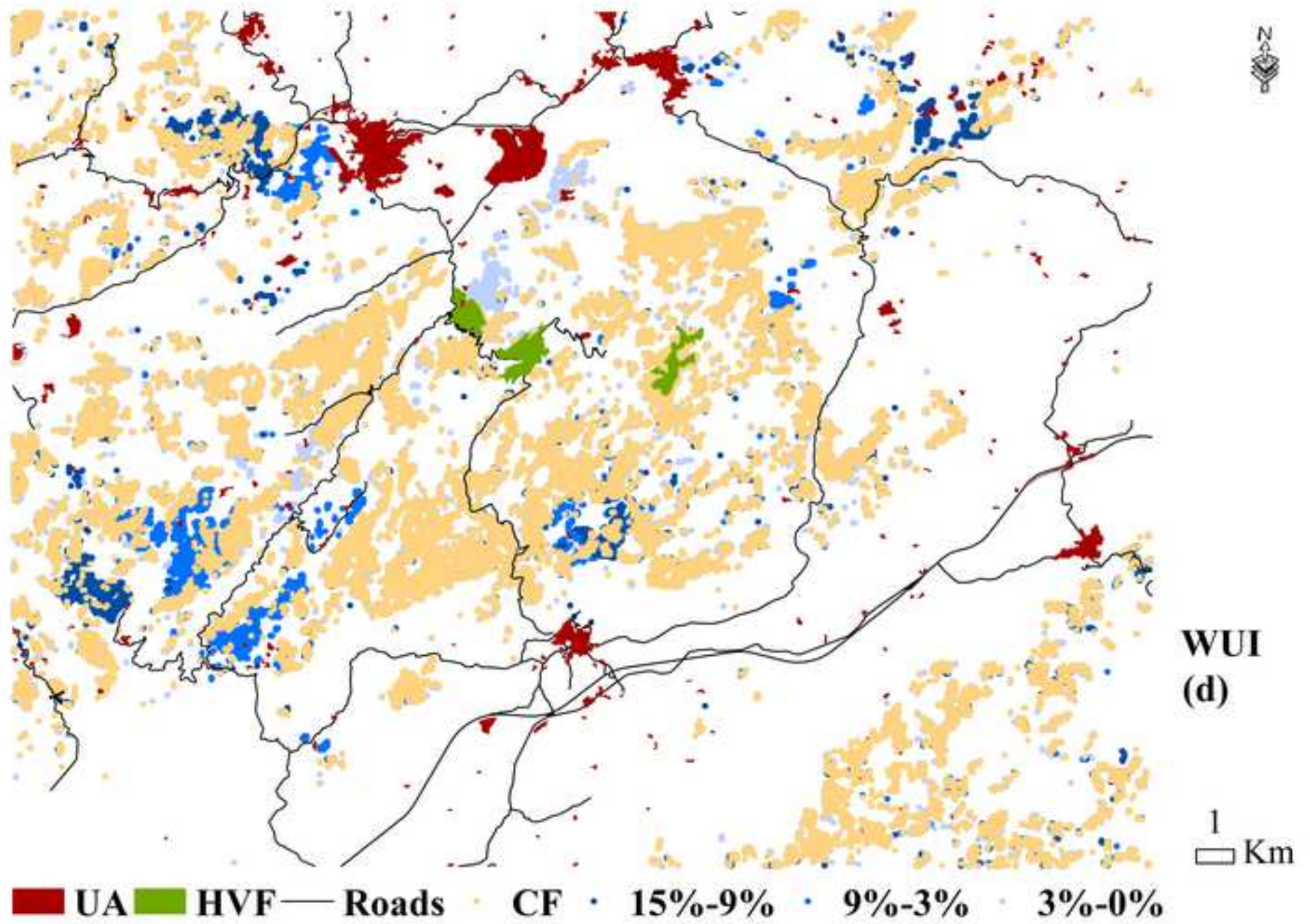


Figure 9

	HECTARES CFL>2.5
TO	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%	

Figure 10**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

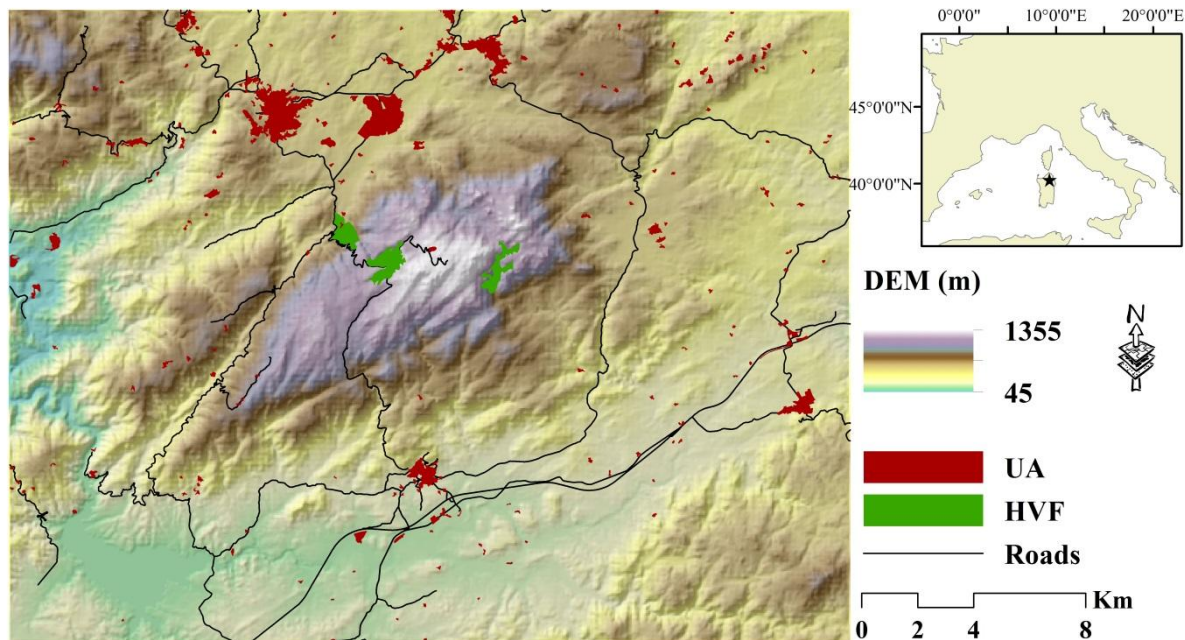
ROADS

	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

Figure 11

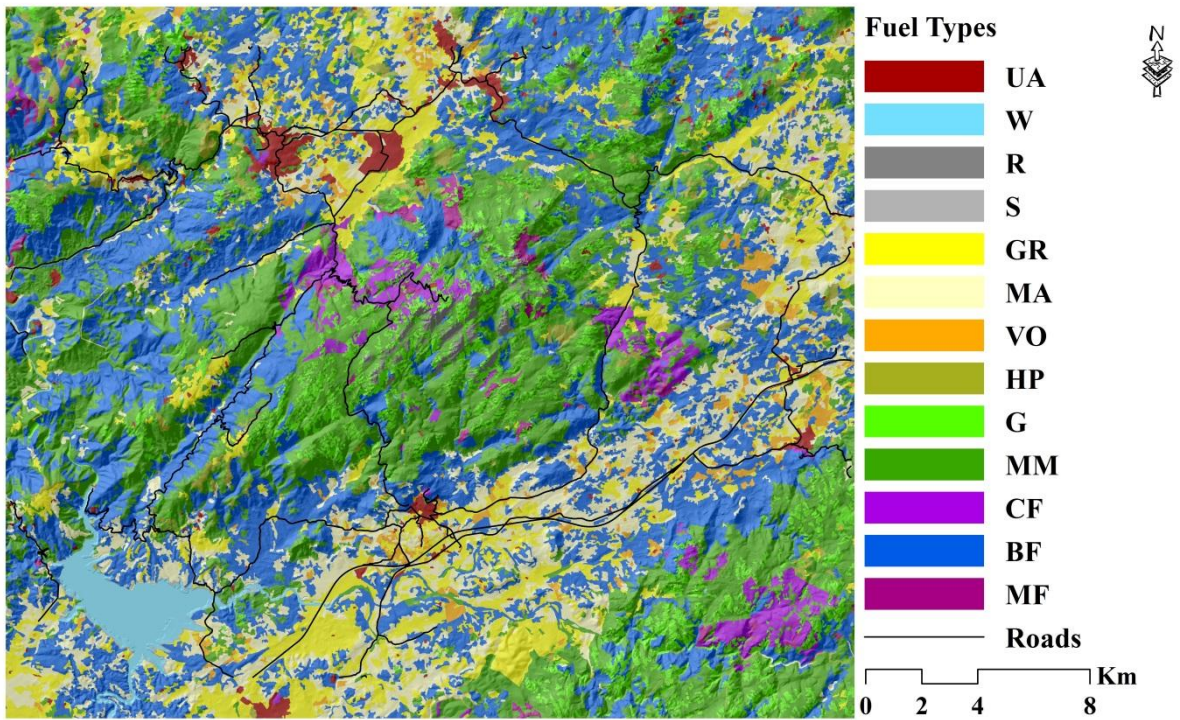
FUEL	NO-TREAT				ROAD-3%		
	BP_avg	CFL_avg	FS_avg	FPI_avg	BP_avg	CFL_avg	FS_avg
Pastures	0.00892006	0.927771	227.3391866	247.8566	0.00867	0.757382	222.2567
Garrigue	0.011306844	1.415257	321.9731628	273.3325	0.010843	1.299297	318.4239
Mediterranean Maquis	0.012799088	2.058522	369.090345	337.8865	0.011297	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
7



8

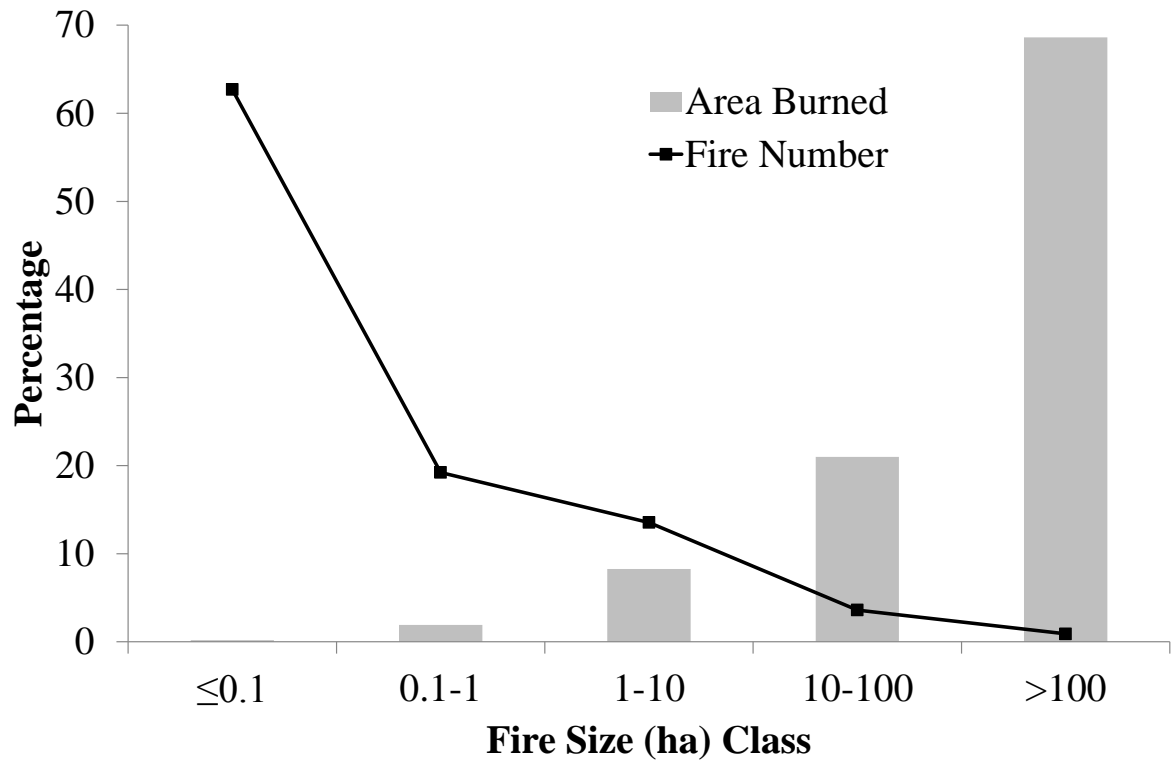
9 Fig. 2. Main fuel types of the study area. UA=urban and anthropic areas; W=water bodies;

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

13



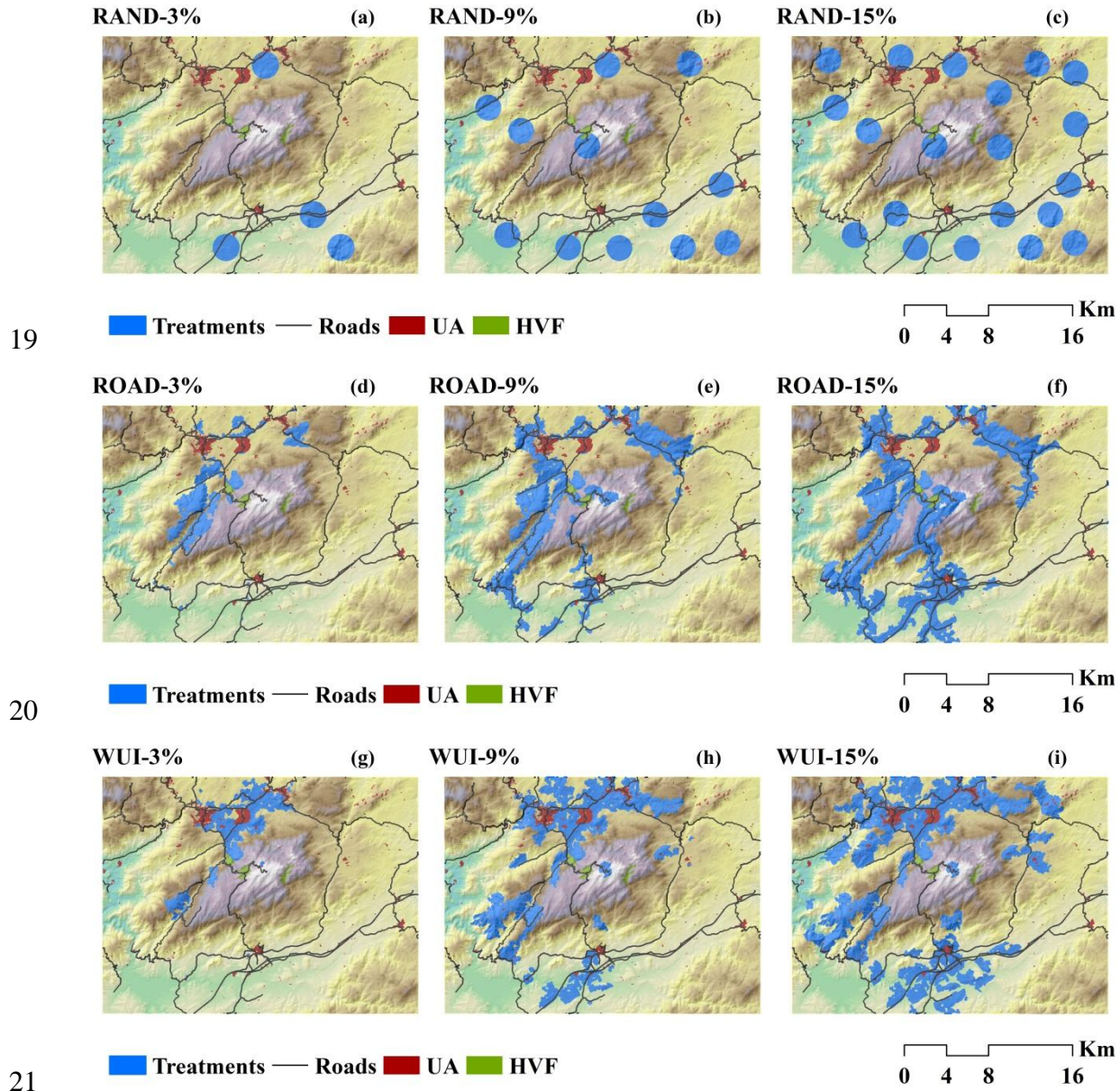
14

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)

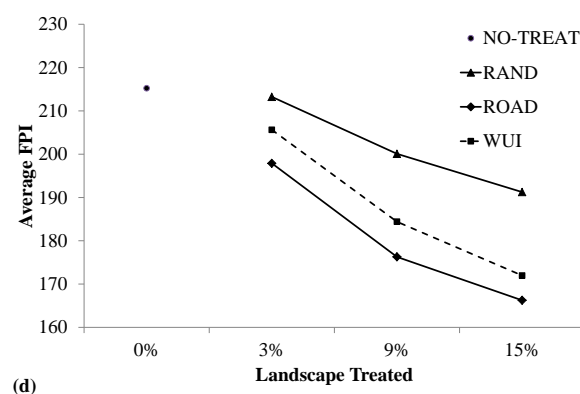
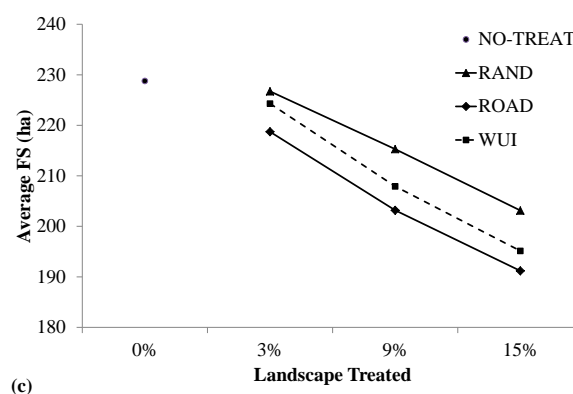
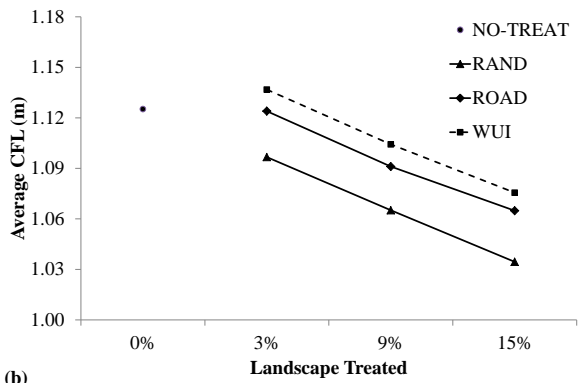
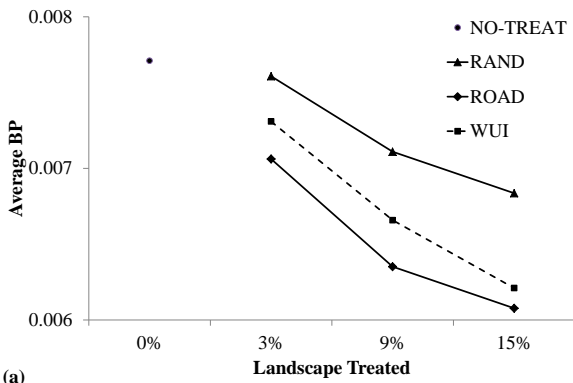
17

18



22 Fig. 4. Maps of the fuel treatment strategies tested (random treatments (RAND, a, b, c), road
23 protection (ROAD, d, f, g), urban and anthropic areas protection (WUI, g, h, i)), considering
24 3%, 9% and 15% of the landscape treated.

25
26
27



28

29

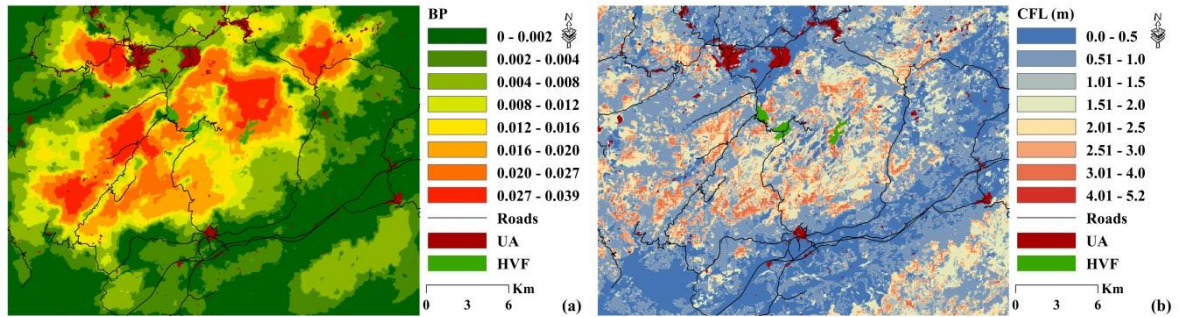
30 Fig. 5. Effect of fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI) and treatment
 31 intensity (3%, 9%, 15%) on average burn probability (BP, a), conditional flame length (CFL,
 32 b), fire size (FS, c) and fire potential index (FPI, d). This analysis was performed considering
 33 the whole landscape.

34

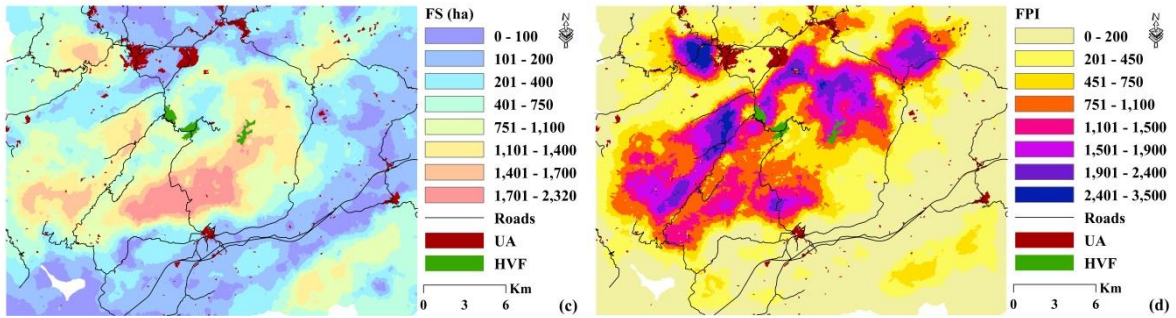
35

36

37



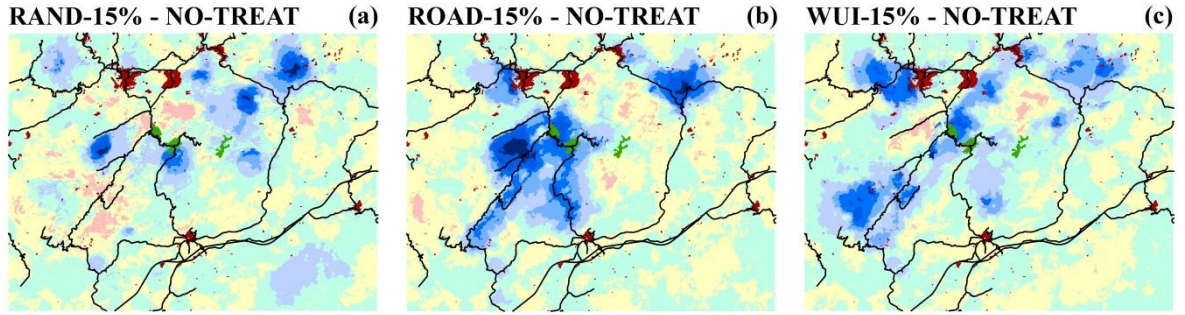
38



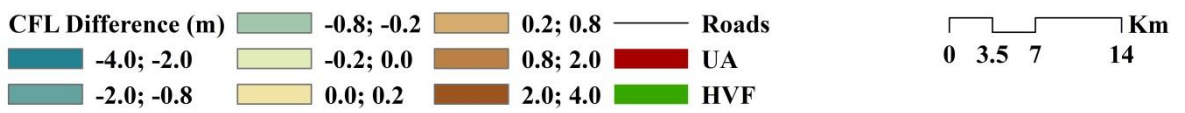
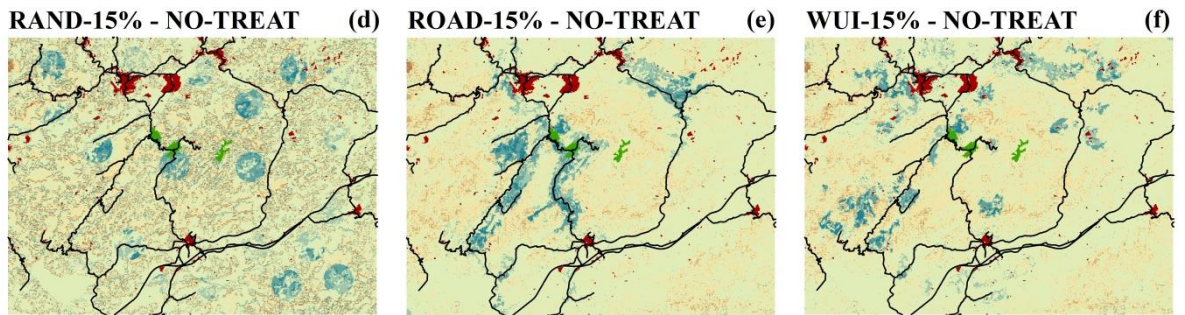
39 Fig. 6. Burn probability (BP, a), conditional flame length (CFL, b), fire size (FS, c), and fire
40 potential index (FPI, d) for the untreated scenario (NO-TREAT).

41

42



43



44

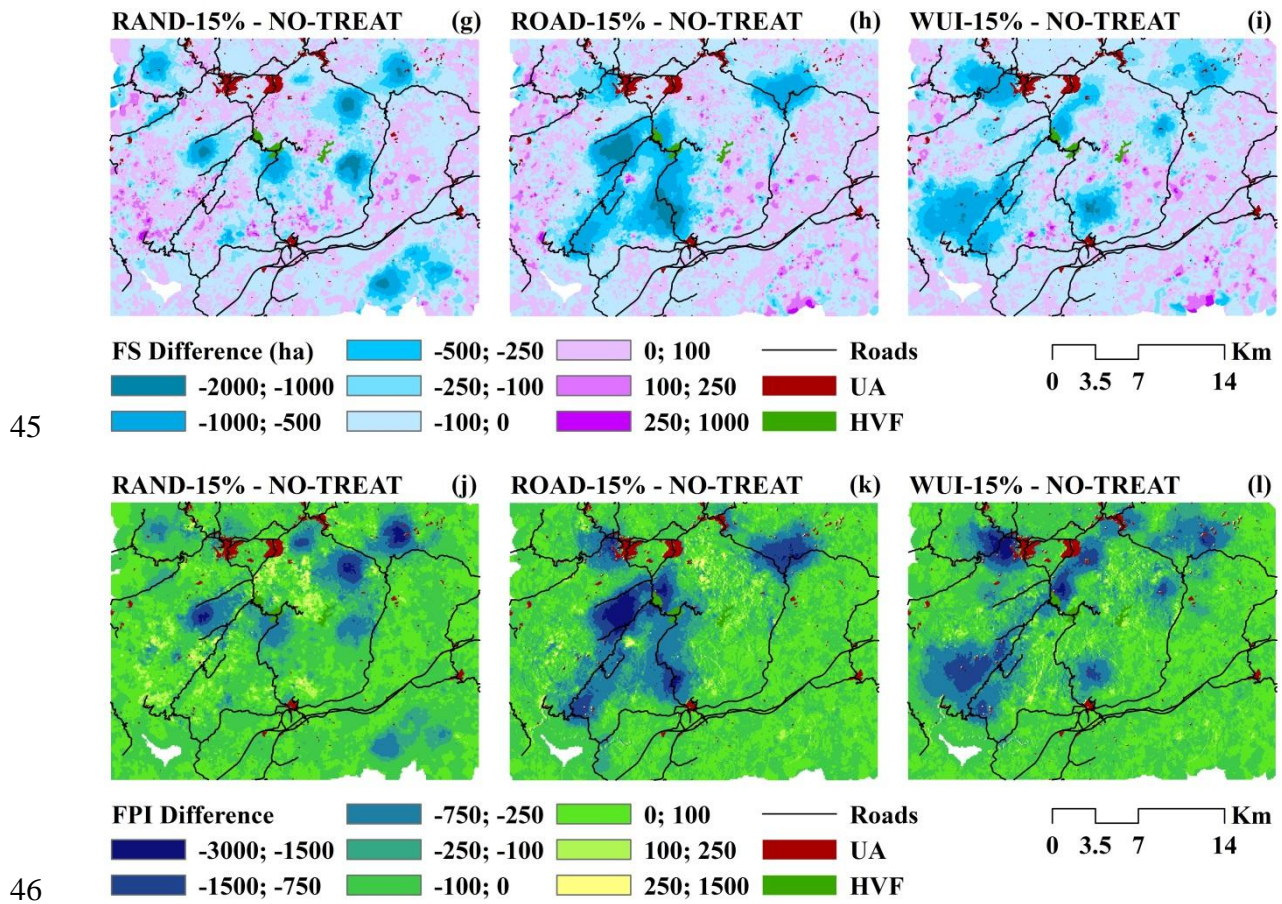
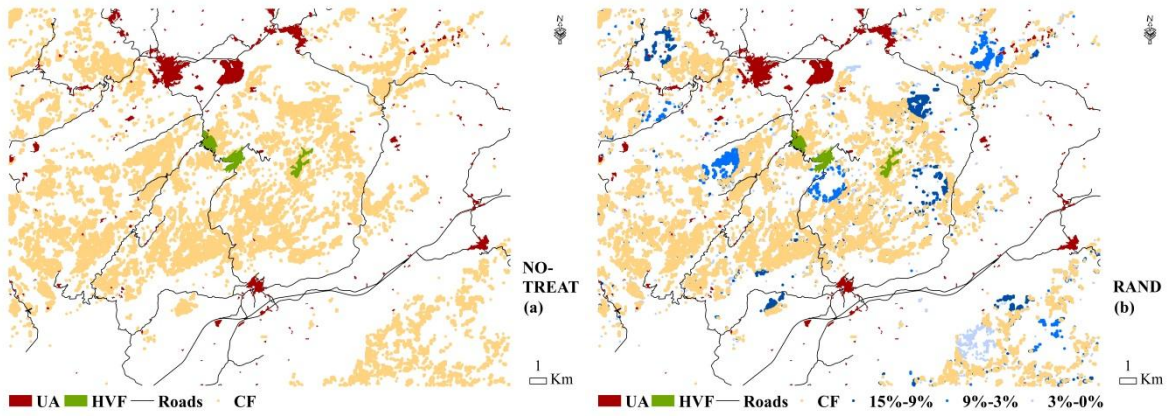
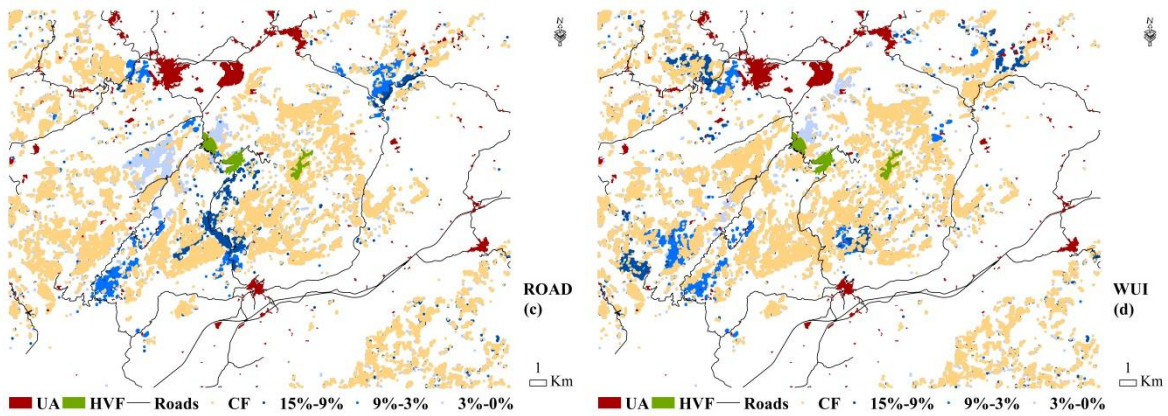


Fig. 7. Differences in BP (a, b, c), CFL (d, e, f), FS (g, h, i) and FPI (j, k, l) between the fuel treatment strategies (RAND, ROAD and WUI, considering the treatment intensity of 15%) and the untreated condition (NO-TREAT).

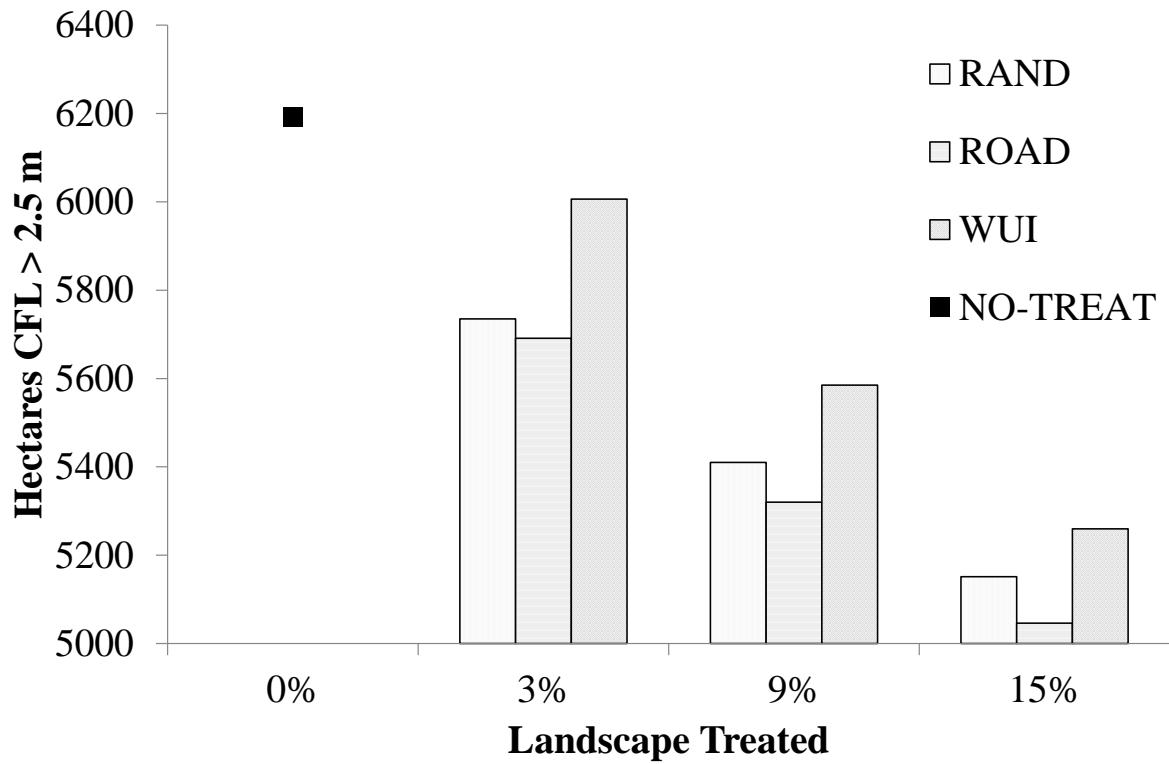
51



52



53 Fig. 8. Potential crown fire (CF) occurrence considering the diverse strategies (NO-TREAT,
54 a; RAND, b; ROAD, c; WUI, d). The areas with different blue color gradations, from light to
55 dark, indicate the reduction of crown fires associated with increasing treatment intensities
56 (3%, 9%, 15% of the landscape treated).

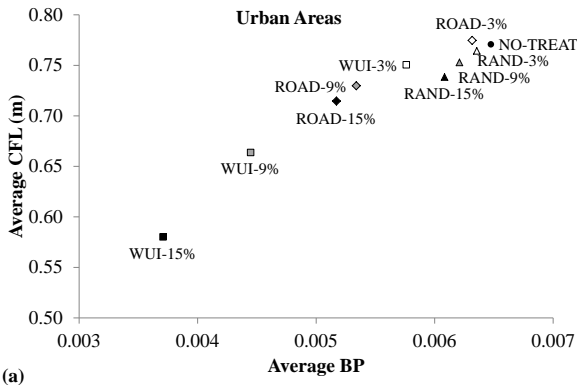


57

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

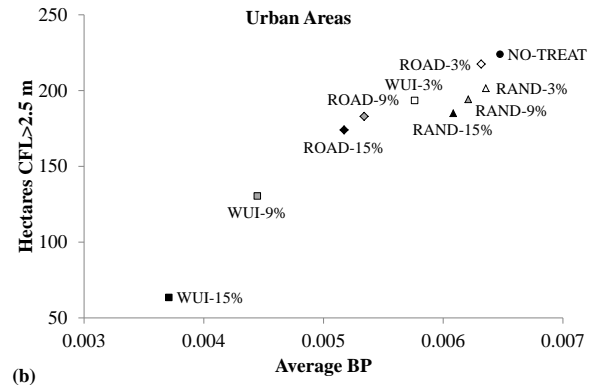
60

61

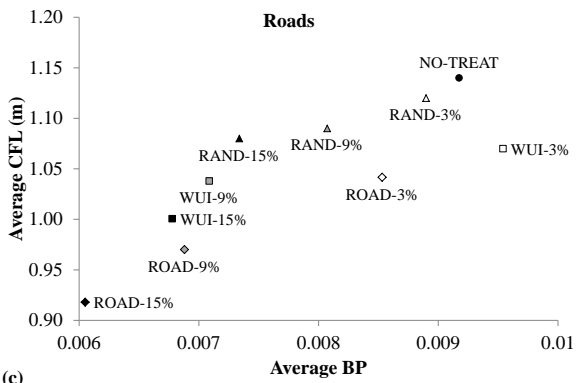


62

(a)

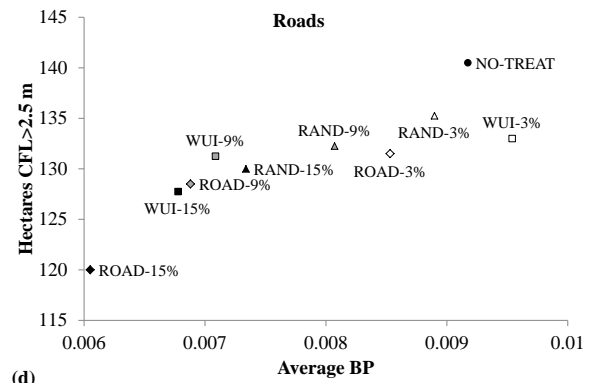


(b)

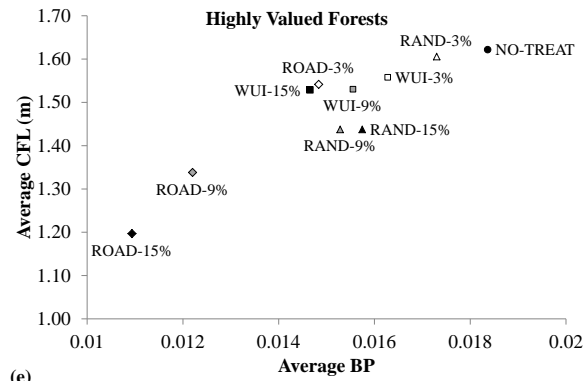


63

(c)

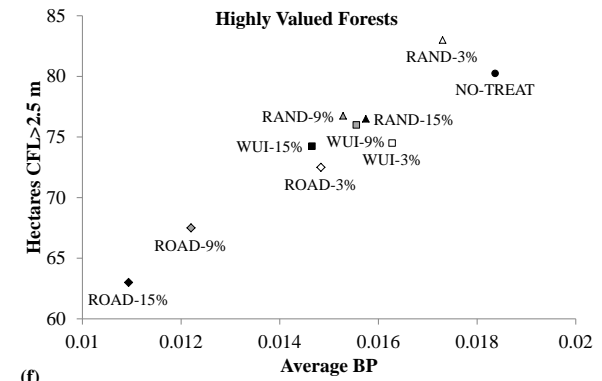


(d)



64

(e)

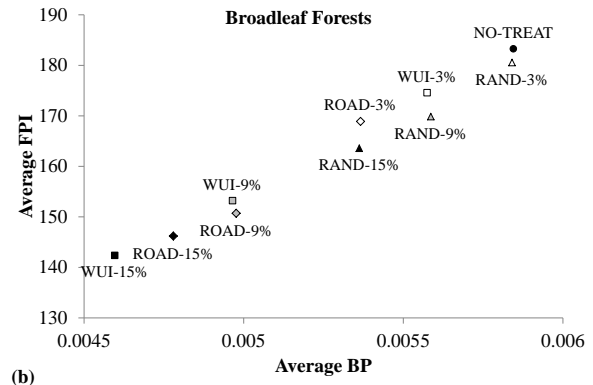
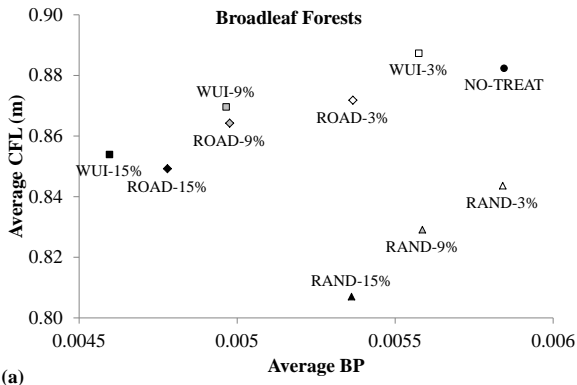


(f)

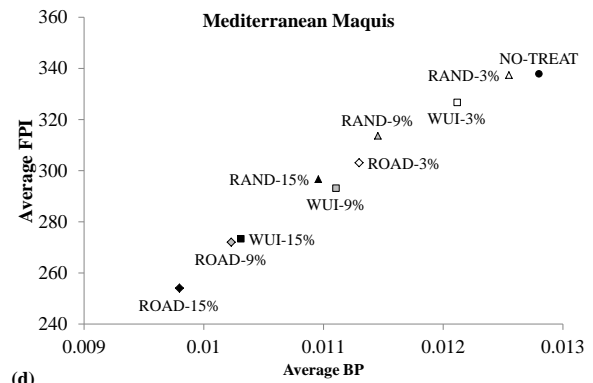
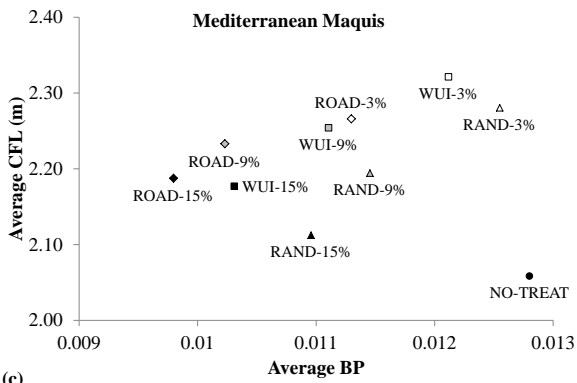
65 Fig. 10. Scatterplots of BP vs. CFL and BP vs. hectares with CFL > 2.5 m in the surroundings
 66 (buffer 150 m) of urban areas (a, b), roads (c, d), and highly valued forests (e, f).

67

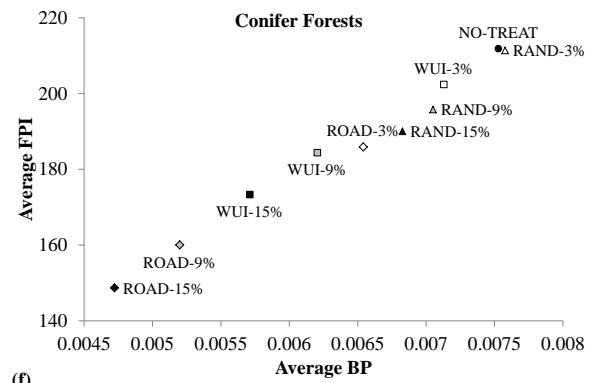
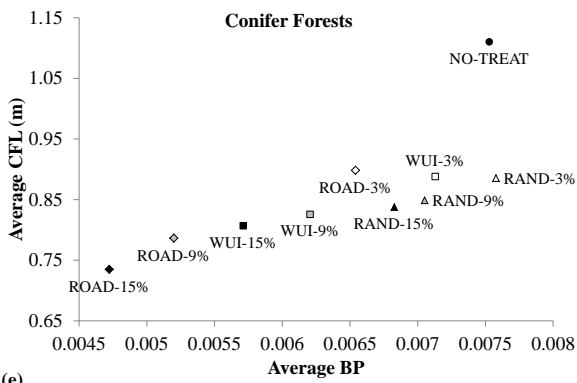
68



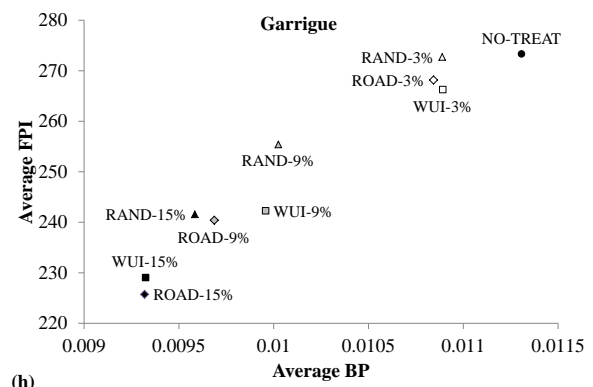
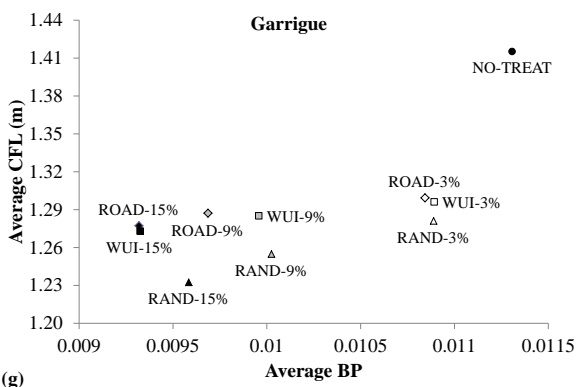
69

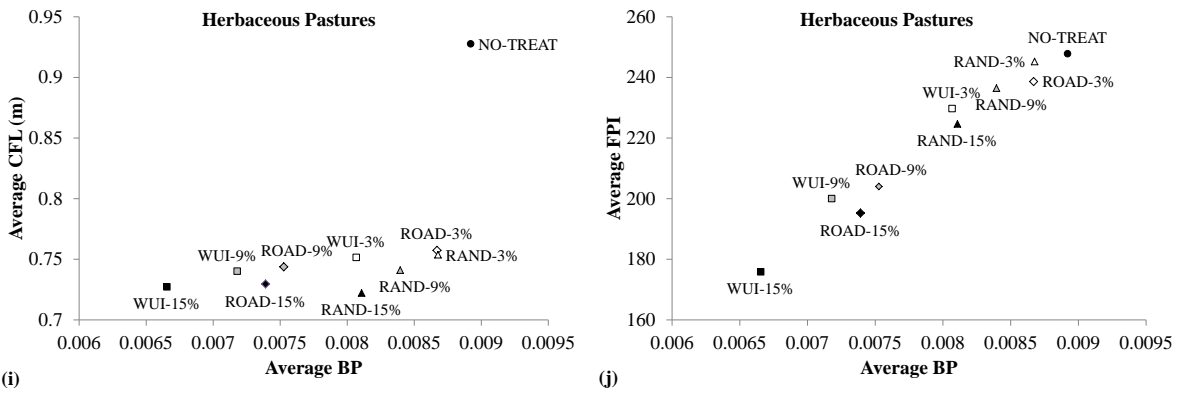


70



71





72

73

74

75

76

77

78

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)