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Abstract

The goal of this work is to evaluate by a modeling approach the effectiveness of alternative fuel treatment strategies to reduce potential losses from wildfires in Mediterranean areas. We compared strategic fuel treatments located near specific human values versus random locations, and treated 3, 9 and 15% of a 68,000 ha study area located in Sardinia, Italy. The 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 study area, using historic weather and fuel moisture conditions (97^{th} percentile). Wildfire 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 and within the fuel management strategies and treatment intensities. The simulated mitigation strategies substantially decreased the average wildfire exposure with respect to the untreated condition, and this effect was unequivocal for all strategies. Increasing the percentage of land treated improved the effectiveness of all fuel treatment strategies. The strategy based on road protection provided the highest performances for several wildfire exposure indicators. The methodology presented in this work can be applied to facilitate the design of fuel management programs and support policy decisions to address growing wildfire risk in the 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.

Keywords

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

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, implementation of socio-economic policies and land uses, and fire suppression activities (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 biophysical variables (Koutsias *et al.* 2010; Lovreglio *et al.* 2012; Oliveira *et al.* 2012; Meddour-Sahar *et al.* 2013; Ager *et al.* 2014*a*; Salis *et al.* 2015). In recent years, the increase and densification of anthropic activities and population in main towns, as well as in coastal zones, has contributed to an increase in fire ignition sources in such areas (Martínez *et al.* 2009; Chas-Amil *et al.* 2013). Moreover, rural exodus and land abandonment during the last decades prompted a rapid natural succession of vegetation in areas previously exploited for 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 development of understory vegetation and ladder fuels in previous timber production areas (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 vegetation complexes (Mazzoleni *et al.* 2004; Palahi *et al.* 2008; Fernandes *et al.* 2014). 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; Xanthopoulos *et al.* 2006; Curt *et al.* 2013). Moreover, a substantial increase in fire suppression costs in the last decade has limited investments in fuel management and fire prevention (Calkin *et al.* 2005; Stephens and Ruth 2005; Prestemon *et al.* 2008; Hand *et al.* 2014). For these reasons, fire managers and policy makers need to adopt the best compromise between fire control and fuel management approaches for the future, while considering that the complete exclusion of wildfires is not a feasible and reasonable strategy in the long term (Keane *et al.* 2008; Moritz *et al.* 2014). In the Mediterranean Basin, fire restoration and management are a challenging proposition since many houses and values intermingle with wilderness and unmanaged lands, and thus managing wildfires for fuel management poses 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 continuity reduction treatments (e.g., prescribed burns and mastication), silvicultural practices to change tree crown structure (e.g., thinning and low-pruning), and the creation of infrastructures and safety areas to facilitate fire suppression activities (e.g., road networks and water points) (e.g.: Bovio 2002; Leone and Signorile 1997; Fernandes and Botelho 2003; Xanthopoulos et al. 2006; Molina *et al.* 2011; Bovio and Ascoli 2013; Zagas *et al.* 2013; Corona *et al.* 2015). Risk mitigation is strongly linked to landscape fuel management and may involve a range of primary targets, strategies and spatial patterns depending on fire 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; Corona *et al.* 2015; Valor *et al.* 2015). Designing feasible strategies is a complicated problem and a number of recent studies have explored appropriate spatial and temporal strategies and the effects of various constraints on their performance in reducing wildfire exposure and risk (Finney 2001; Agee 2002; Duguy *et al.* 2007; Finney *et al.* 2007; Wei *et al.* 2008; Ager *et al.* 2010; Elia *et al.* 2014; Chung 2015; Vogler *et al.* 2015). Most studies examining fuel 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 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.

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

Material and Methods

Study area

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

The natural vegetation is mostly characterized by *Quercus ilex* and *Quercus suber* L. woods, as well as high and dense Mediterranean maquis. In the hilly and mountainous areas of Monte Limbara, the most representative shrub types are *Erica arborea* L. and *Arbutus unedo* L., 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 artificial plantations of *Pinus pinea* L., *Pinus pinaster* Aiton, and *Pinus nigra* ssp. *laricio* Poir. On the whole, shrublands and forests occupy about 46,000 ha of the study area, which 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).

Wildfire data

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 coordinates, municipality and date of ignition, and estimated fire size. Overall, from 1980 to 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 from mid-July to late August. About 95% of the fires were smaller than 10 ha, while only 4.5% of ignitions were responsible for 90% of the total area burned in the study period (Fig. 3). The main fire causes in the study area are related to arson and negligence, while lightning fires do not exceed 3% of the events. For this reason, roads and surroundings of villages, as 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).

Input data for wildfire modeling

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 obtained from 10-m digital elevation data of the island (www.sardegnageoportale.it). Surface and canopy fuels were interpreted from the 2008 Sardinian Land Use Map (Uso del Suolo 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 either a standard or custom model (Table 1, Fig. 3, Anderson 1982; Scott and Burgan 2005; Arca *et al.* 2009). For forest fuels, we used different fuel models depending on the elevation of the area, using 600 m as threshold of reference. Canopy bulk density, canopy base height and canopy height of the wooded areas were estimated using as reference *Quercus suber* L. and, at high elevation, *Quercus ilex* L. stands, considering the data from the National Inventory of Forests and Forest Carbon Sinks (INFC 2005).

Fuel moisture content (FMC) for the 1-h and 10-h time lag dead fuel was determined by the 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 associated to large wildfires in Sardinia. The main wind direction scenarios were developed from wildfire reports, weather data, and personal communication of the Sardinia Forest Service of the study area. The wind directions mostly related to wildfires in the period 1980-2010 were from NW and W, both of which characterized about 65% of days with wildfires. 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 characterized by high average wind speed (above 18 km h^{-1}). For the wildfire simulations, wind speed was held constant (35 km h^{-1}) and was derived calculating the wind speed 97th

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

Fuel management scenarios

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

Overall we generated 10 fuel management scenarios, which consisted of the no-treatment (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 total area to 3% (≈ 2,000 ha), 9% (≈ 6,000 ha), and 15% (≈ 10,000 ha) of the landscape (Fig. 4). We then applied three spatial treatment priorities, two based on alternative strategies of burn probability (BP) reduction to prioritize protection of urban and anthropic areas (WUI) 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.*

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.

The urban and residential protection scenario (WUI) prioritized stands surrounding urban and 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 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 (ROAD) focused on protecting the main roads of the study areas, hypothesizing buffer areas around these values. The road network represents the most relevant fire ignition zone in Sardinia, and also in this case the sites to be treated are easily accessible. We obtained spatial data on urban and anthropic areas and roads from Regione Sardegna (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.

Wildfire simulations

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.

For each treatment alternative, as well as for the untreated landscape, we simulated 25,000 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 were developed to reflect likely scenarios associated with escaped large wildfires in the study area based on wildfire history and personal communication with Forest Service and experts. The assumption was that, from a risk standpoint, the primary concern for fire management is the combination of escaped wildfires and extreme weather conditions, since these fires are responsible for the most damage and suppression activities are commonly ineffective against these events (Finney 2005, Calkin *et al.* 2014). Simulations were performed at 25 m 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, SW, S) associated with the largest fires, with the relative incidence, were used as input as previously defined. No suppression efforts were considered, since their effect in extreme 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.

The wildfire simulations generated a burn probability (BP) and a frequency distribution of flame lengths (FL) in twenty 0.5 m classes for each pixel. The burn probability is the probability a pixel will burn at a given flame length interval, given an ignition in the study 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 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 file and using the inverse distance weighting (search radius 1,000 m) of ArcMap Spatial Analyst. The combination of number of fire ignition points and average fire size for each cell allowed to derive the fire potential index (FPI) (Salis *et al.* 2013), which measures the potential of a pixel to originate large fires. Crown fire potential occurrence in forest areas was identified for a given pixel and fuel model when the CFL value was higher than the canopy base height value. Moreover, to evaluate the areas where suppression capabilities of terrestrial forces were overwhelmed by fire intensity, we considered 2.5 m as flame length threshold to operate in safety in the fire front (Andrews *et al.* 2011). In addition, a buffer area of 150 m surrounding roads, urban areas and high valued forests was considered to test the 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.

Results

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

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 areas treated decreased significantly the average values of BP, CFL, FS and FPI for all fuel treatment strategies (Fig. 5 and Table 2). Average BP among the scenarios and treatment levels ranged from a low of 6.08 10^{-3} with ROAD-15% treatment to a high of 7.61 10^{-3} under RAND-3% treatment, being NO-TREAT equal to 7.71 10^{-3} (Table 2). Likewise, the highest FS and FPI average values were observed in RAND-3% treatment, while the lowest values were obtained with ROAD-15% (Table 2). Meanwhile, average CFL reached a maximum of 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 behavior profiles was enhanced, and this was particularly evident for average BP, FS and FPI (Table 2). Furthermore, random strategy effects in mitigating fire exposure were significantly lower as compared to both urban and road protection (Fig. 7 and Table 2), except for CFL. Applying the treatment to 15% of the areas resulted in a higher reduction of BP, FS and FPI average values for both ROAD and WUI protection strategies (about 20%, 15% and 20%, respectively) (Table 2 and Fig. 7). As far as average CFL is concerned, the differences between strategies were much slighter, although RAND showed the highest percent reduction 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 lower with respect to NO-TREAT, while for FPI RAND-3% was not statistically different 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.

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

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 highly efficient in protecting the neighboring of these values, while random fuel management was 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 high fire intensity (average CFL>2.5 m). Furthermore, only in a few cases (with 3% of the total landscape treated), the protection of valued resources was not improved by the treatments with respect to NO-TREAT. Specifically, urban areas neighboring were very 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 instance, in comparison with NO-TREAT, WUI-15% reduced average BP of about 43%, average CFL of about 25%, and the hectares with CFL>2.5 m of 72%. On the contrary, RAND strategies were inefficient in mitigating fire exposure nearby urban areas (Fig. 10). In the surroundings of roads, ROAD treatments maximized the reduction in exposure factors, although for this target the differences among strategies were less evident than for urban areas protection. In detail, ROAD-15%, which was the best strategy in limiting exposure nearby roads, showed reduction in BP, CFL and hectares with CFL>2.5 m, with respect to 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 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%, while the other strategies were less adequate (Fig. 10).

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 of average BP and CFL for all vegetation types. In fact, average CFL was reduced with respect to NO-TREAT by every treatment for all types of vegetation, except for broadleaf forests with WUI-3%, for herbaceous pastures and for Mediterranean maquis, while a 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 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. Mediterranean maquis showed the highest average fire intensity values among fuel types (CFL ranged from about 2.05 to 2.30 m), while the lowest fire intensity was observed with grasslands (CFL between 0.32 and 0.39 m) (Fig. 11).

Discussion and Conclusions

Quantitative exposure and risk assessment based on wildfire spread models to analyze potential effectiveness of fuel management strategies on losses from wildfires have been presented in many recent papers (Finney 2001, 2006; Ager *et al.* 2007, 2010, 2013; Finney *et al.* 2007; Parisien *et al.* 2007; Miller *et al.* 2008; Moghaddas *et al.* 2010; Thompson and 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 leveraged to improve fuel management and planning in the Mediterranean Basin. This work represents the first application of fire spread modeling methods to quantify tradeoffs from alternative landscape fuel treatment strategies in Mediterranean ecosystems. Our results suggests that in Mediterranean areas fuel treatment strategies can potentially reduce average fire exposure (assessed by BP, CFL, FS, and FPI, crown fire potential, and hectares with flame length above 2.5 m). As expected, the effect of the fuel treatments on reducing wildfire 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.

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

Overall, the ROAD protection strategies were the most efficient in reducing average BP, FS and FPI at landscape scale, while RAND treatments maximized average CFL reductions. The 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).

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

The use of the flame length threshold of 2.5 m for effective control efforts of hand tools and equipment in the fire head (Andrews *et al.* 2011; Alcasena *et al.* 2015*a*) coupled with the CFL outputs allowed delineation of the areas where ground-based fire suppression is not 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 operations (e.g.: prioritizing the use of aerial forces in specific portions of the landscape; optimization of the fire crews distribution in the field), and may inform fuel treatment locations in order to limit the areas that overwhelm terrestrial force suppression capacity. 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.

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).

The methods and findings of this work can guide the development of strategies to reduce 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 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 ecosystems can benefit from fuel treatments. Furthermore, an effort in collecting data and information on the effectiveness of fuel treatments in limiting fire events and on the potential of reducing fuel load and structure is underway to expand this approach to other 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 critical points of fire exposure and management, and thus may help defining and optimizing the strategies and spatial location of fuel treatments.

Acknowledgements

This work was funded by several sources including the "GEMINA" Project (MIUR/MATTM no. 232/2011), the "Extreme" Project (Sardinia Reg., CRP-25405, LR 7/2007), the "Sughera" Project (Sardinia Reg., Tender 2013 LR 7/2007) and the "Modeling approach to evaluate fire risk and mitigation planning actions" Project (POR SARDEGNA FSE 2007–2013, Asse IV Capitale umano, Linea di Attivita` l.3.1).

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Tables

Table 1. Fuel model data used for the wildfire simulations. A different combination of fuel models was used depending on elevation (ELEV) and fuel treatment activity (TREAT). CH = 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

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 (8.28E-03)	1.125ab (0.825)	564.88a (472.09)	531.43a (564.44)
RAND-3%	7.61E-03b (8.29E-03)	1.097cd (0.823)	559.82b (475.51)	526.53a (568.80)
RAND-9%	7.11E-03d (7.77E-03)	1.065e (0.818)	531.55d (464.42)	494.03c (539.37)
RAND-15%	6.84E-03e (7.61E-03)	1.034f (0.812)	501.56f (448.34)	472.22d (523.41)
ROAD-3%	7.06E-03d (7.57E-03)	1.124b (0.822)	540.04c (464.45)	488.61c (515.26)
ROAD-9%	6.35E-03g (6.86E-03)	1.091d (0.813)	501.66f (441.38)	435.26f (454.48)
ROAD-15%	6.08E-03i (6.74E-03)	1.065e (0.803)	472.05h (407.64)	410.49h (437.21)
WUI-3%	7.31E-03c (7.69E-03)	1.137a (0.830)	553.80b (471.38)	507.74b (534.19)
WUI-9%	6.66E-03f (7.11E-03)	1.104c (0.819)	513.35e (440.48)	455.31e (473.02)
WUI-15%	6.21E-03h (6.81E-03)	1.076e (0.807)	481.80g (416.96)	424.62g (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 $p < 0.05$

Figure 1

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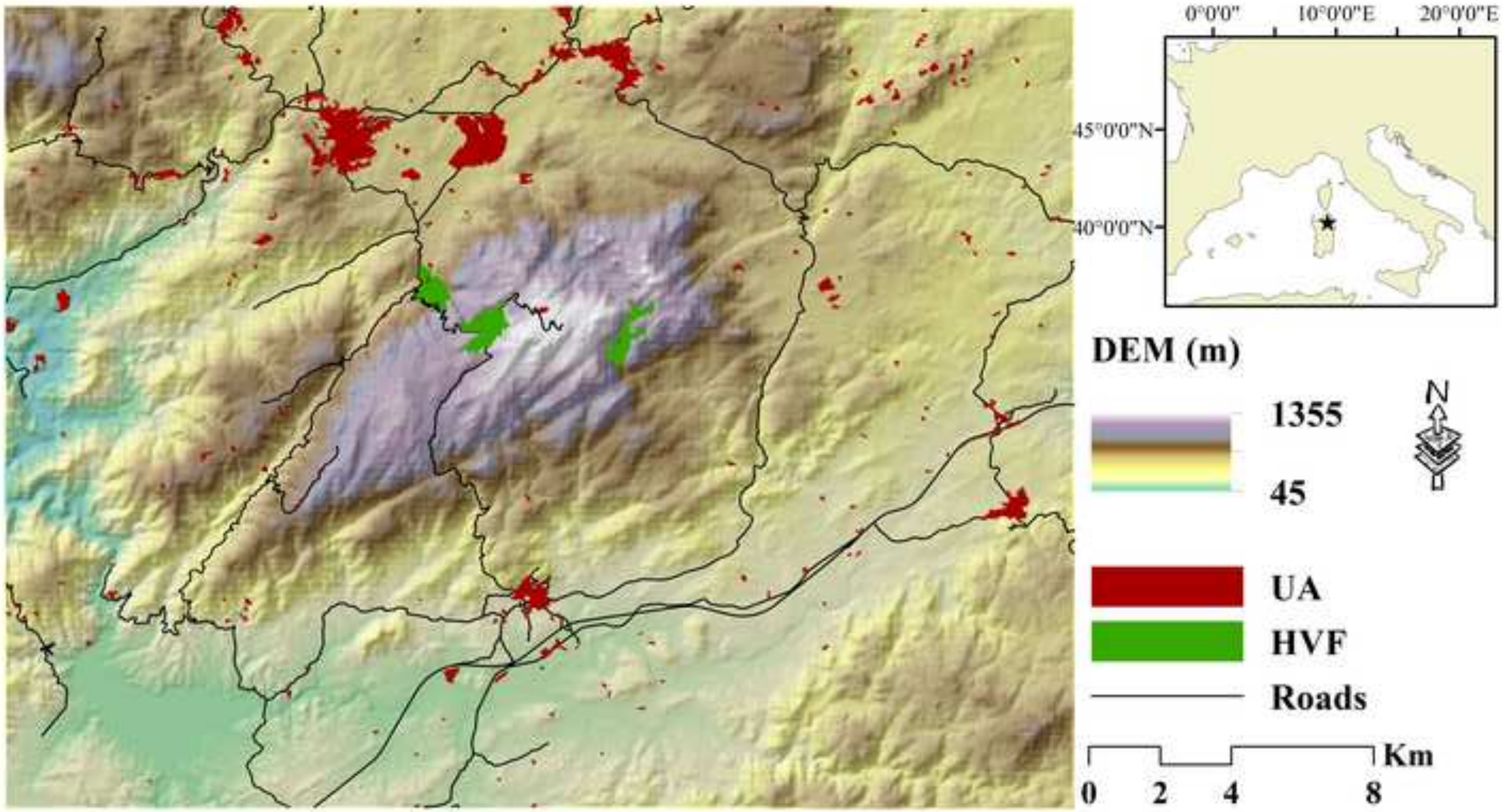

Figure 2
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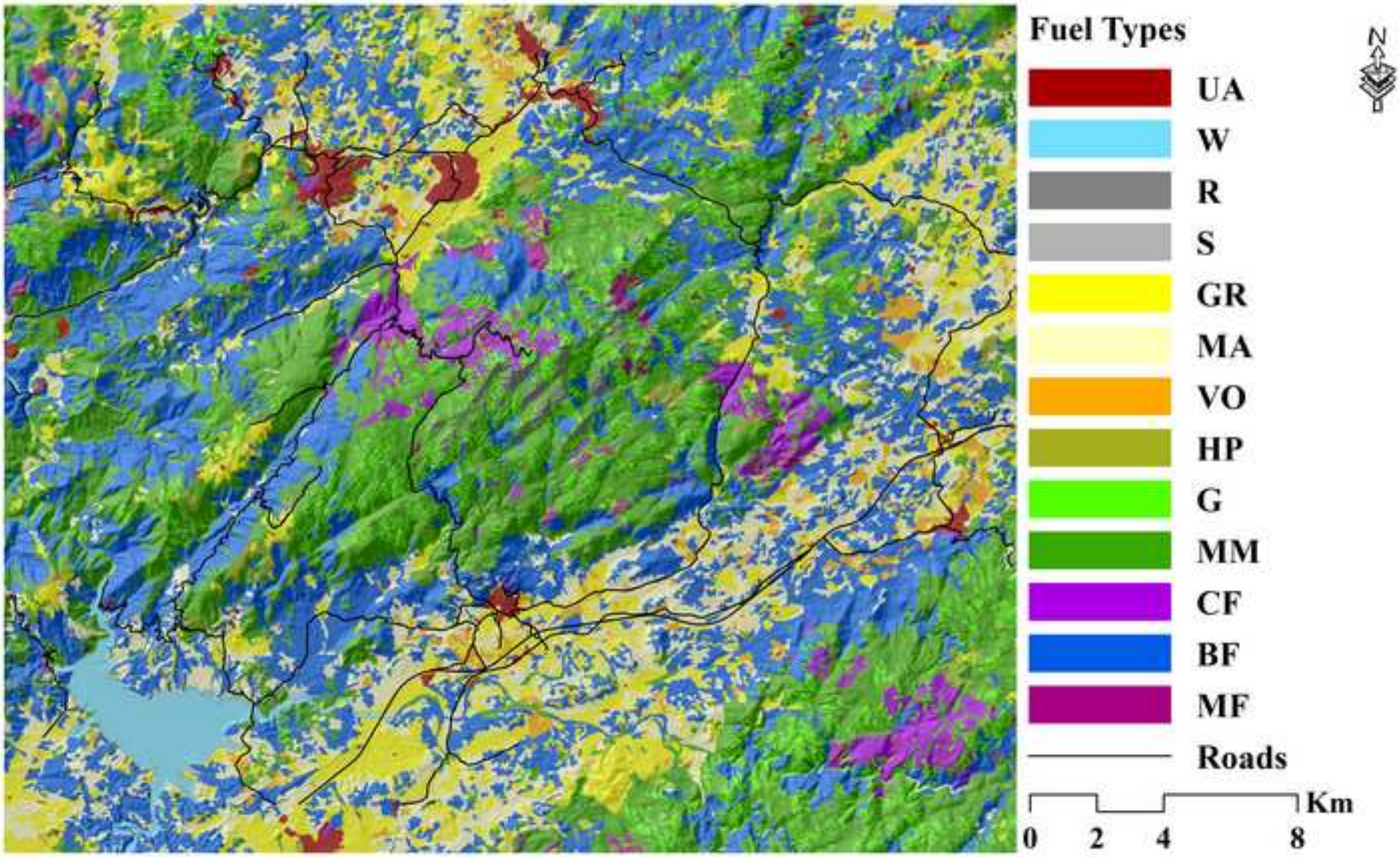

Figure 3

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
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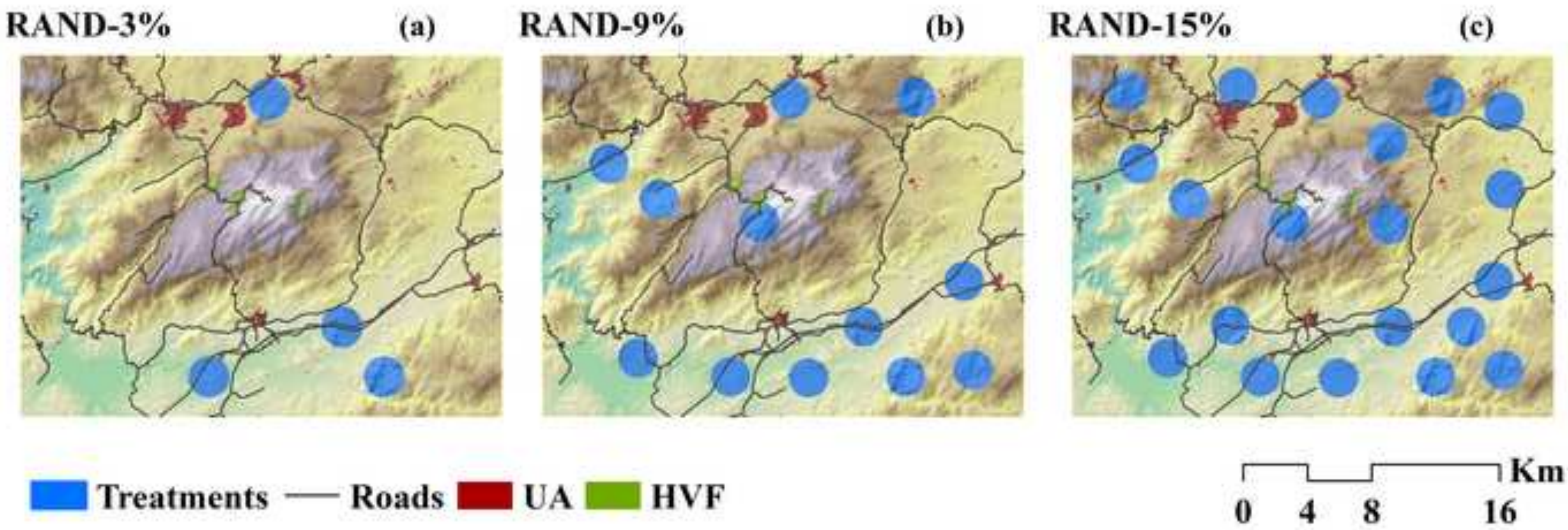

Figure 4b
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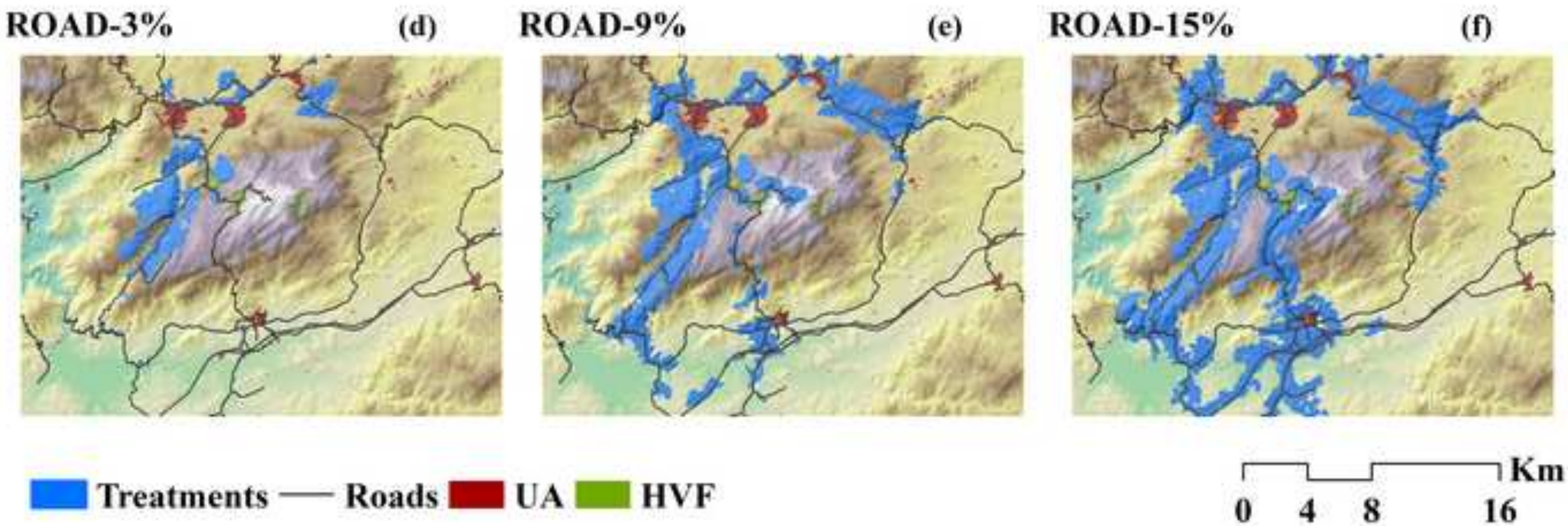

Figure 4c
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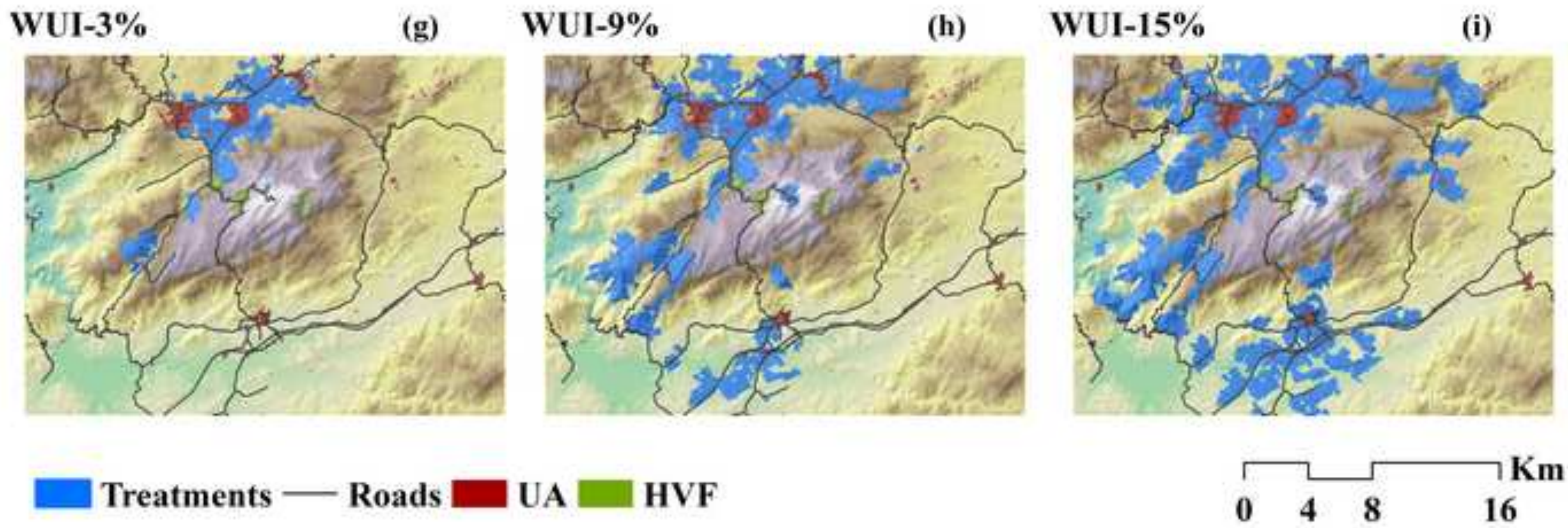

Figure 5

	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	

	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	166.248	
WUI		205.634	184.401	171.972	

	0%	3%	9%	15%	
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	

	0%	3%	9%	15%	
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
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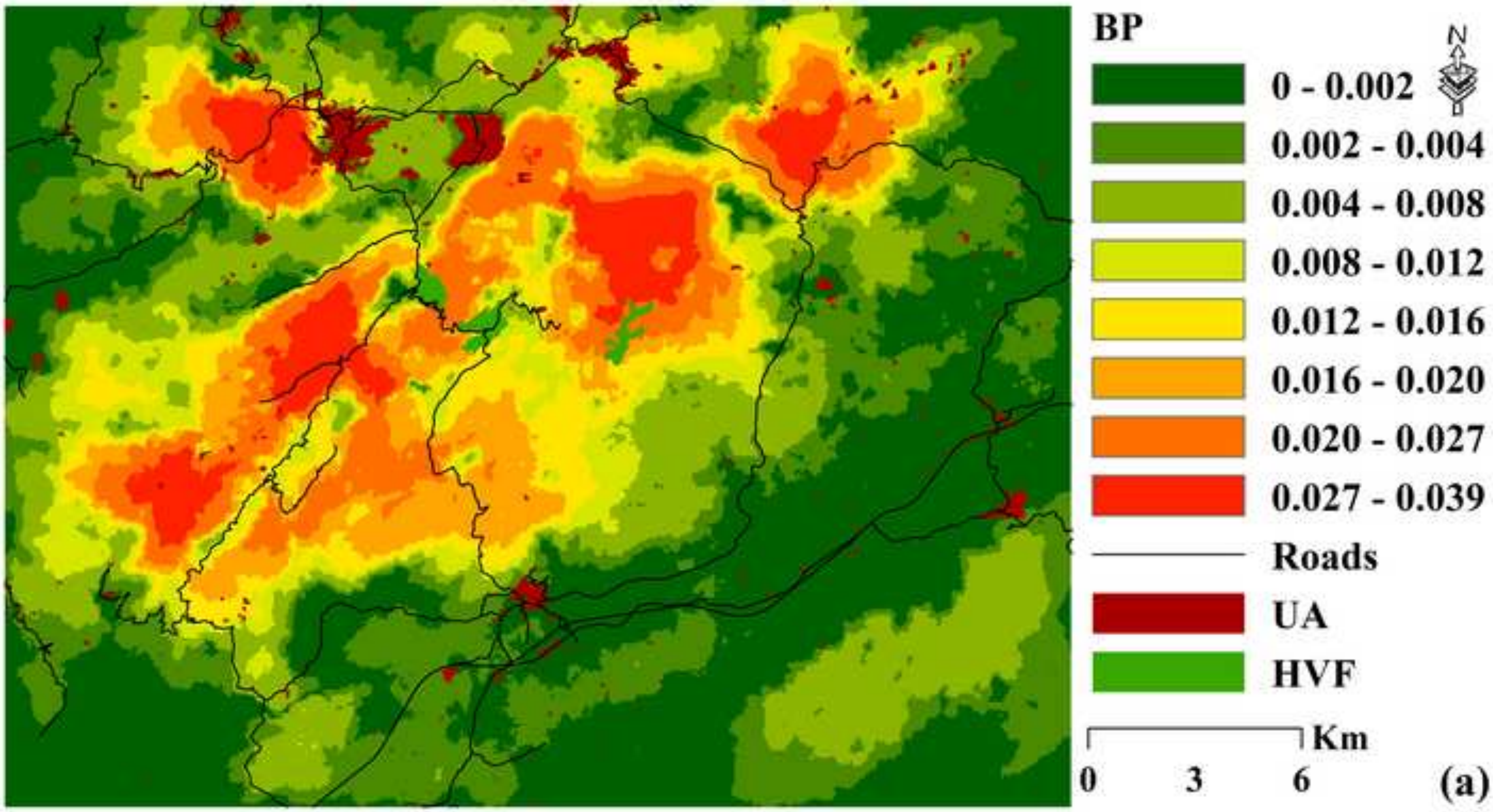

Figure 6b
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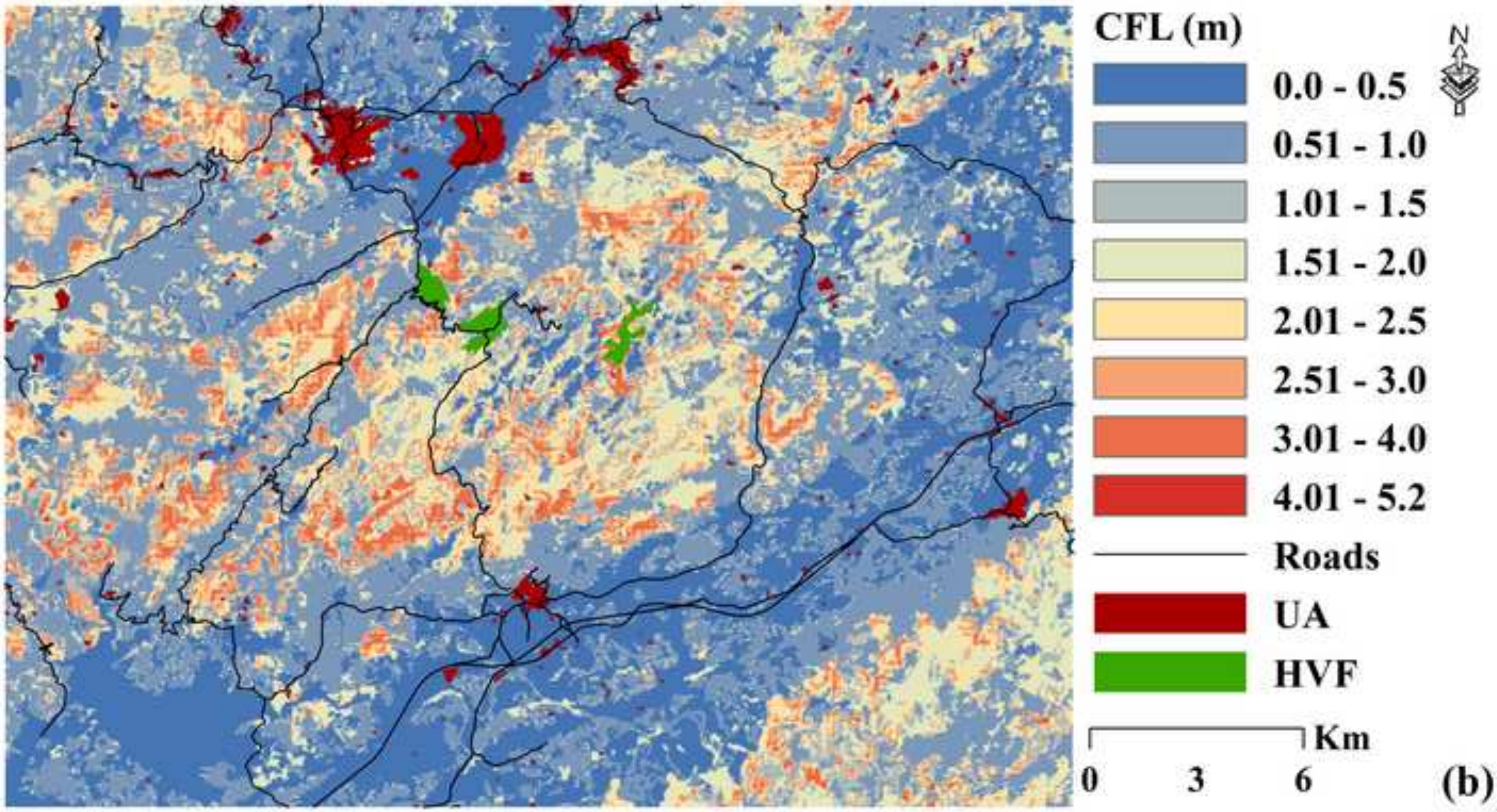

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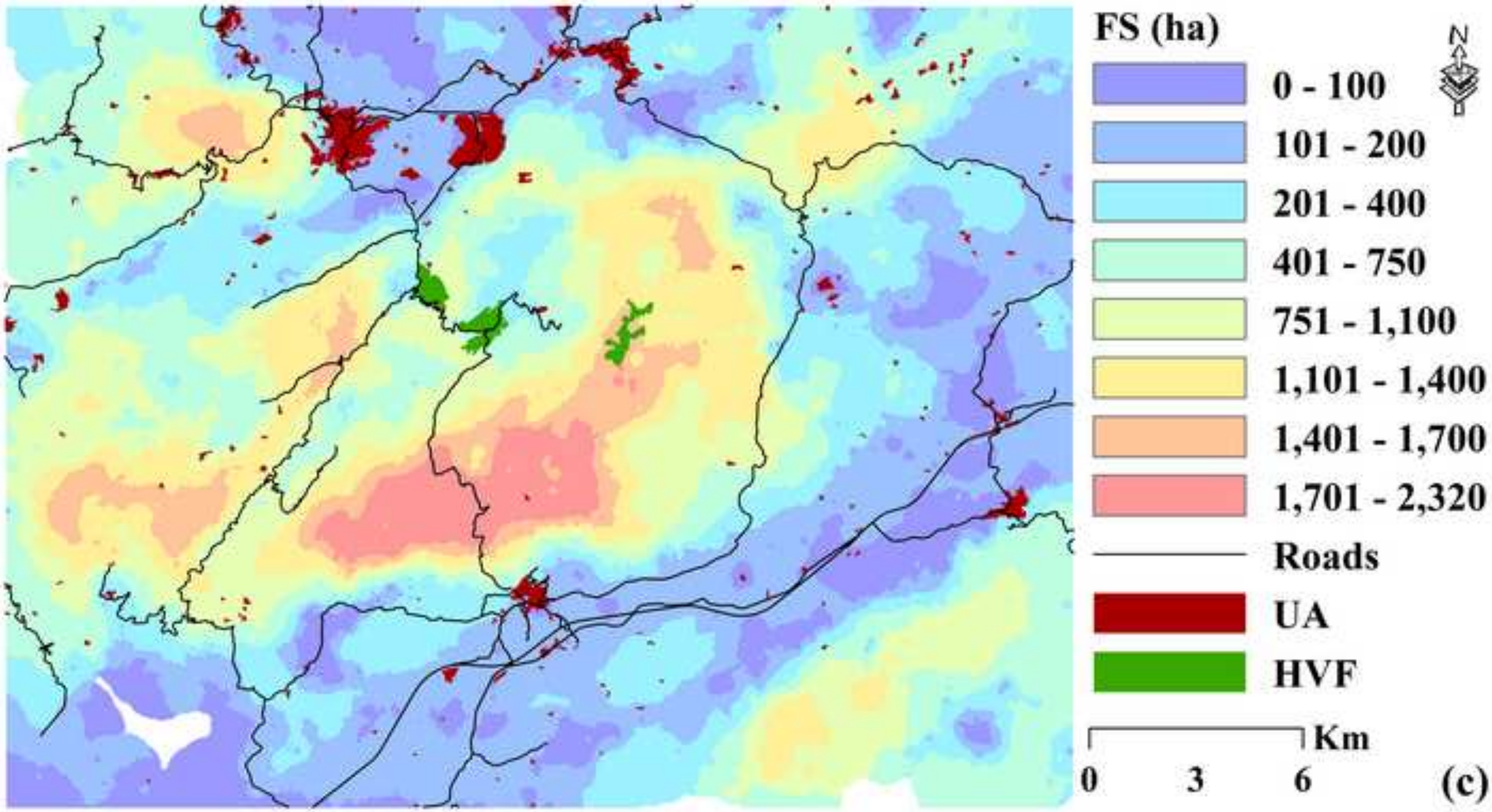

Figure 7a

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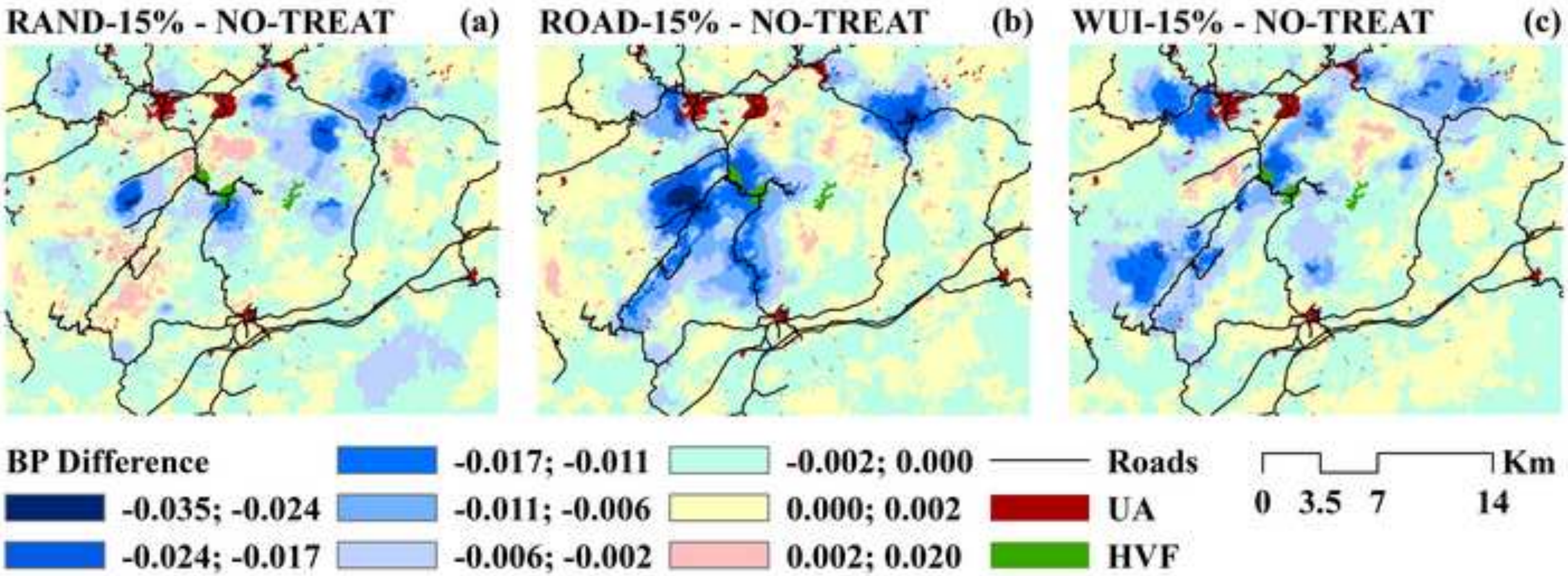

Figure 7b
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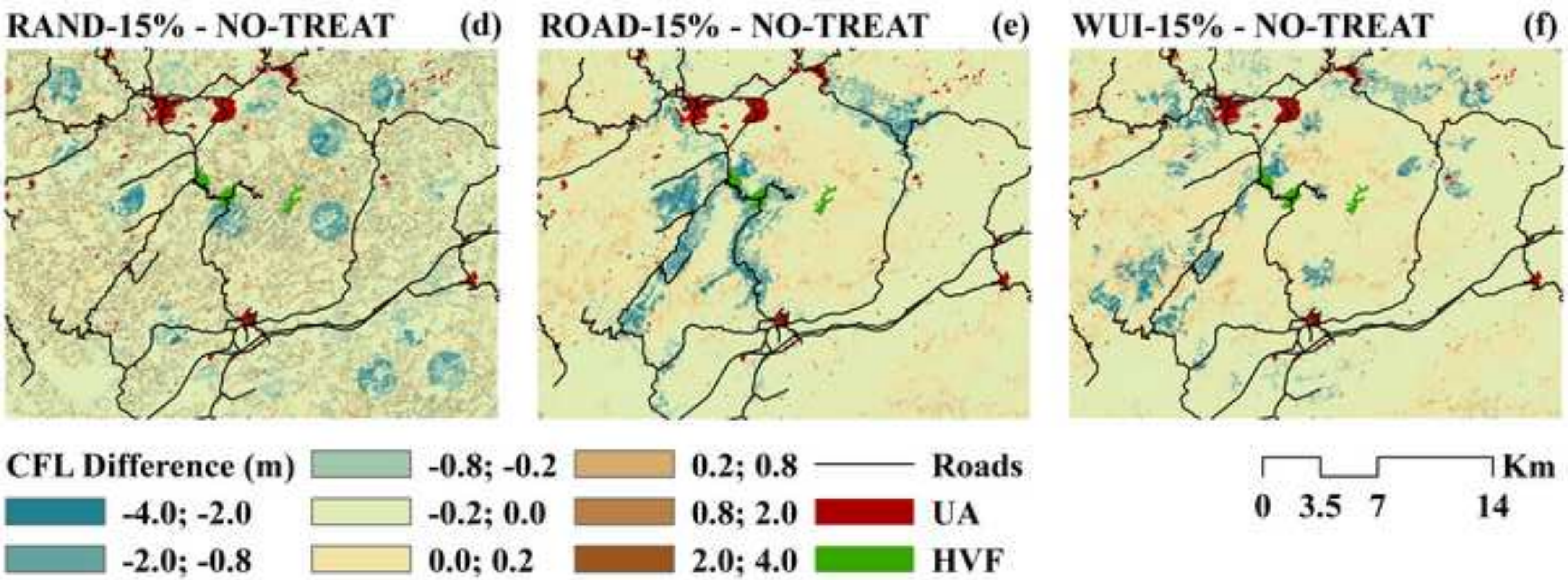

Figure 7c

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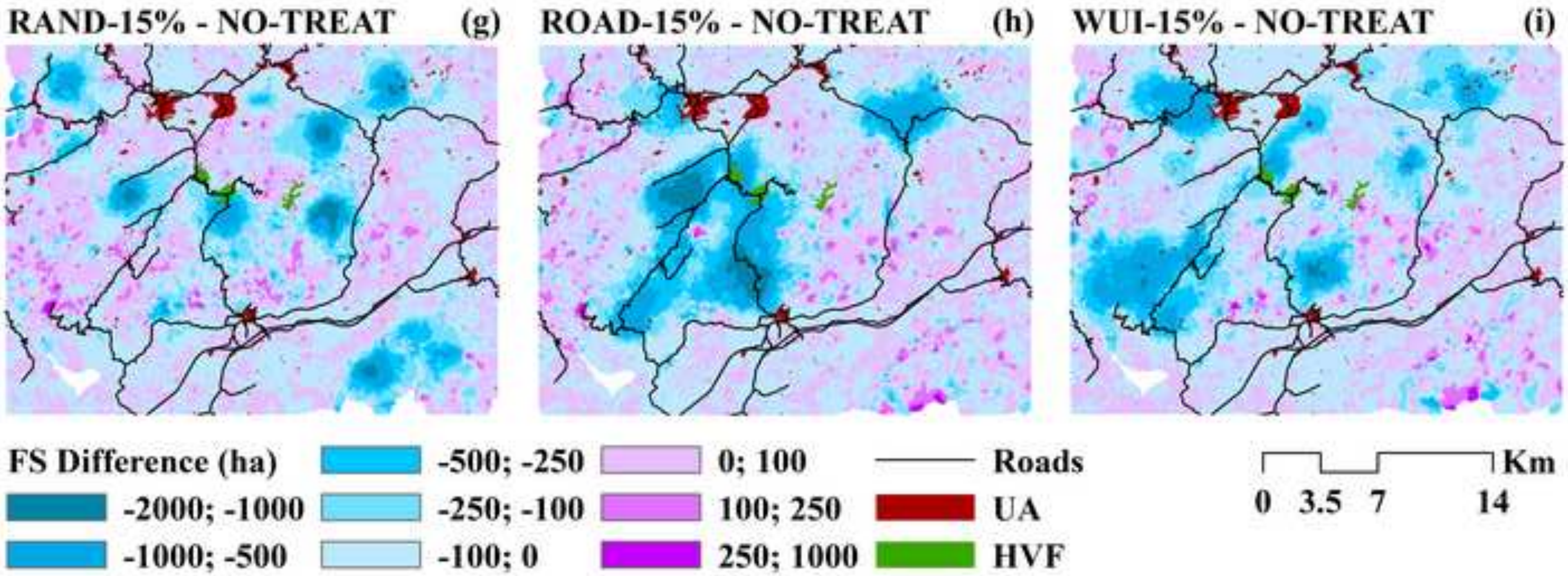

Figure 7d

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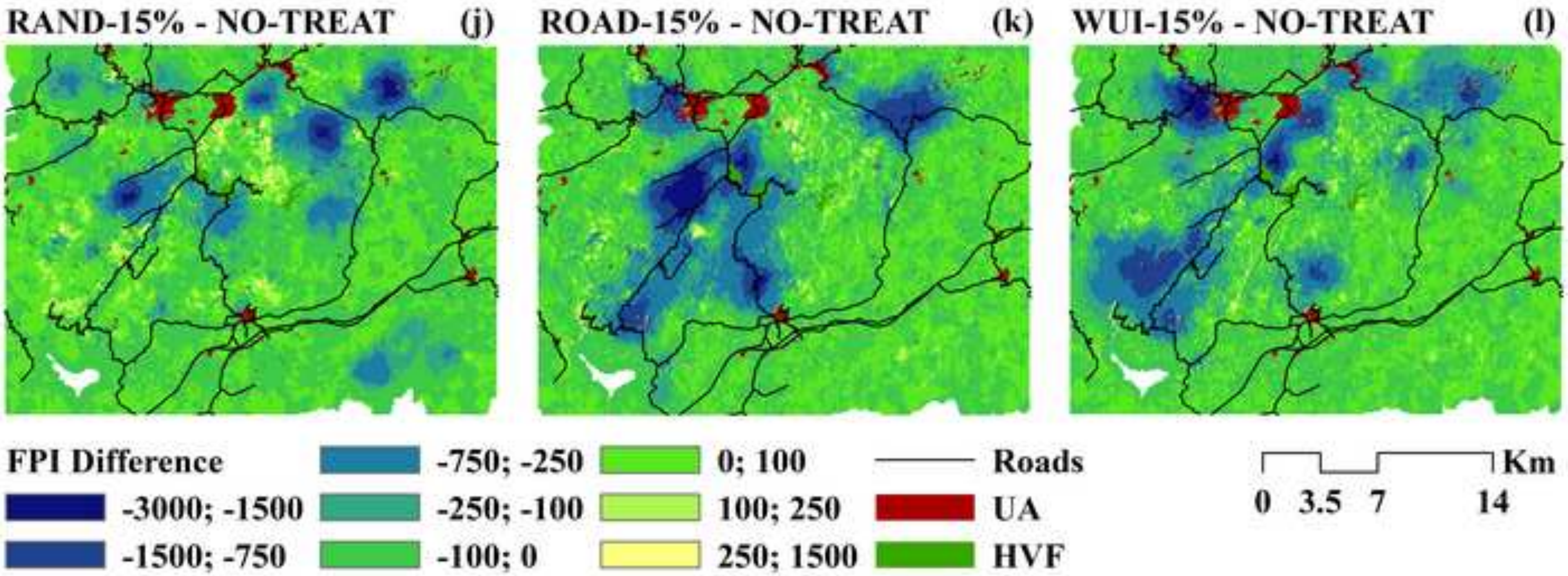

Figure 8a
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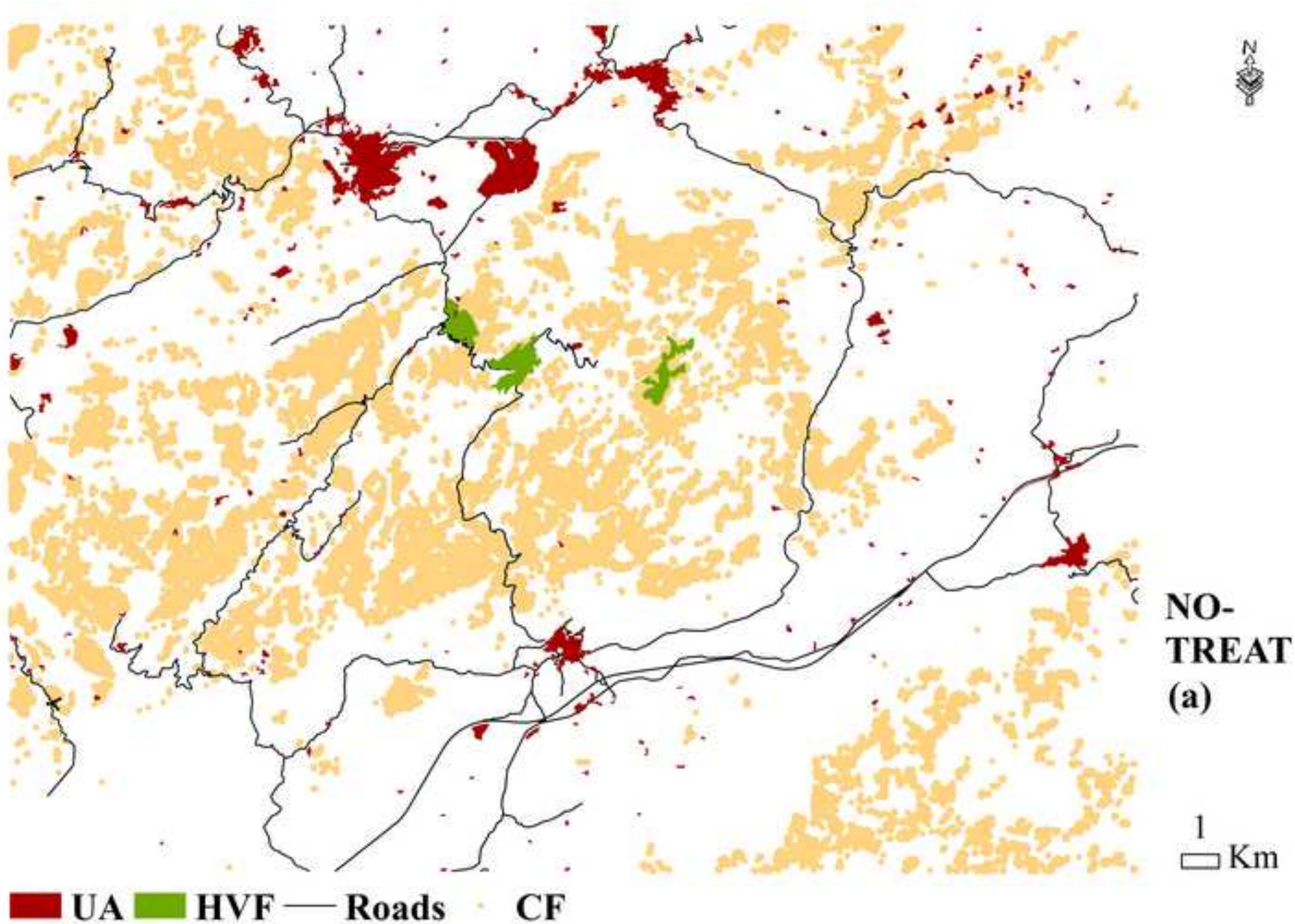

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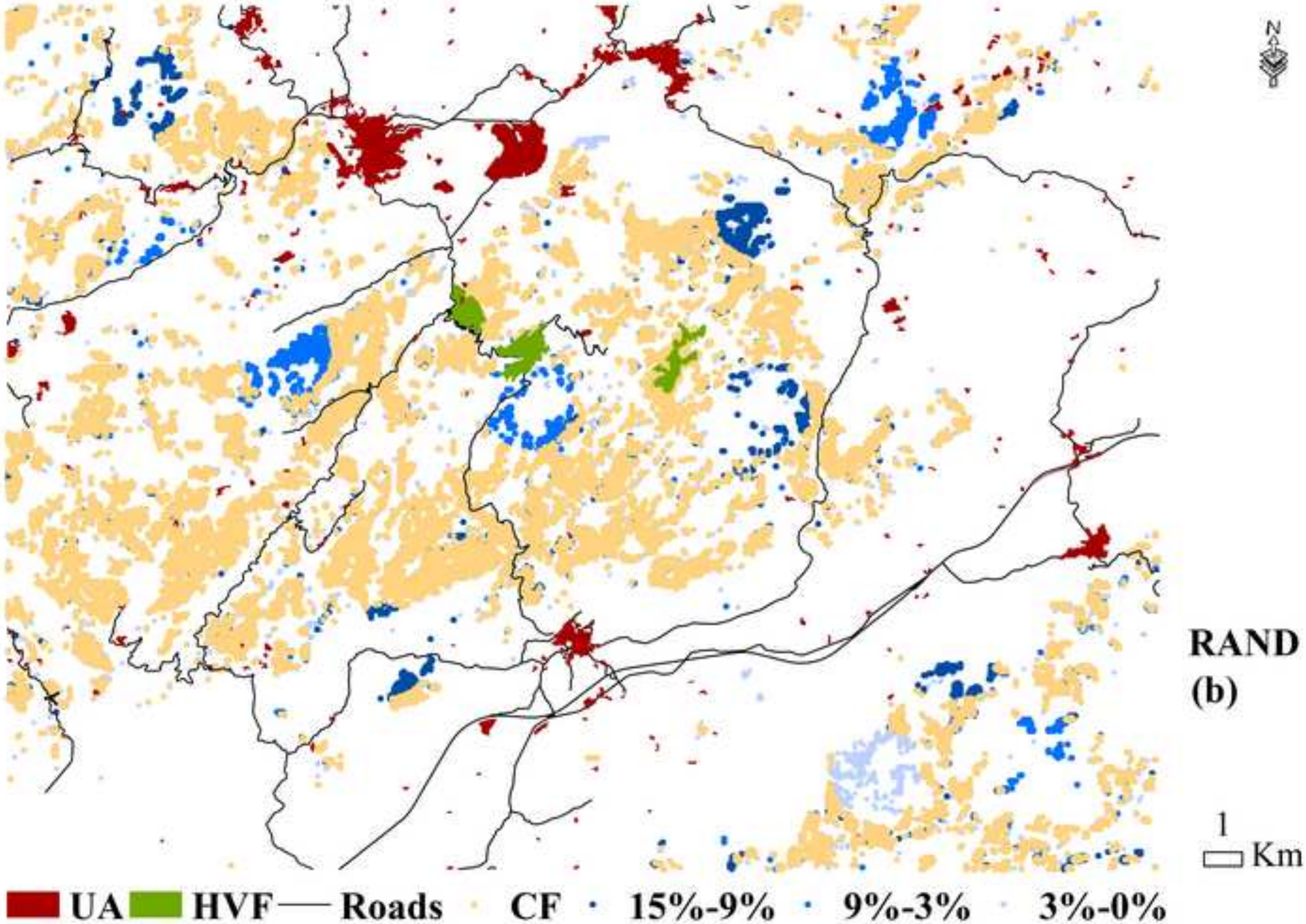

Figure 8c

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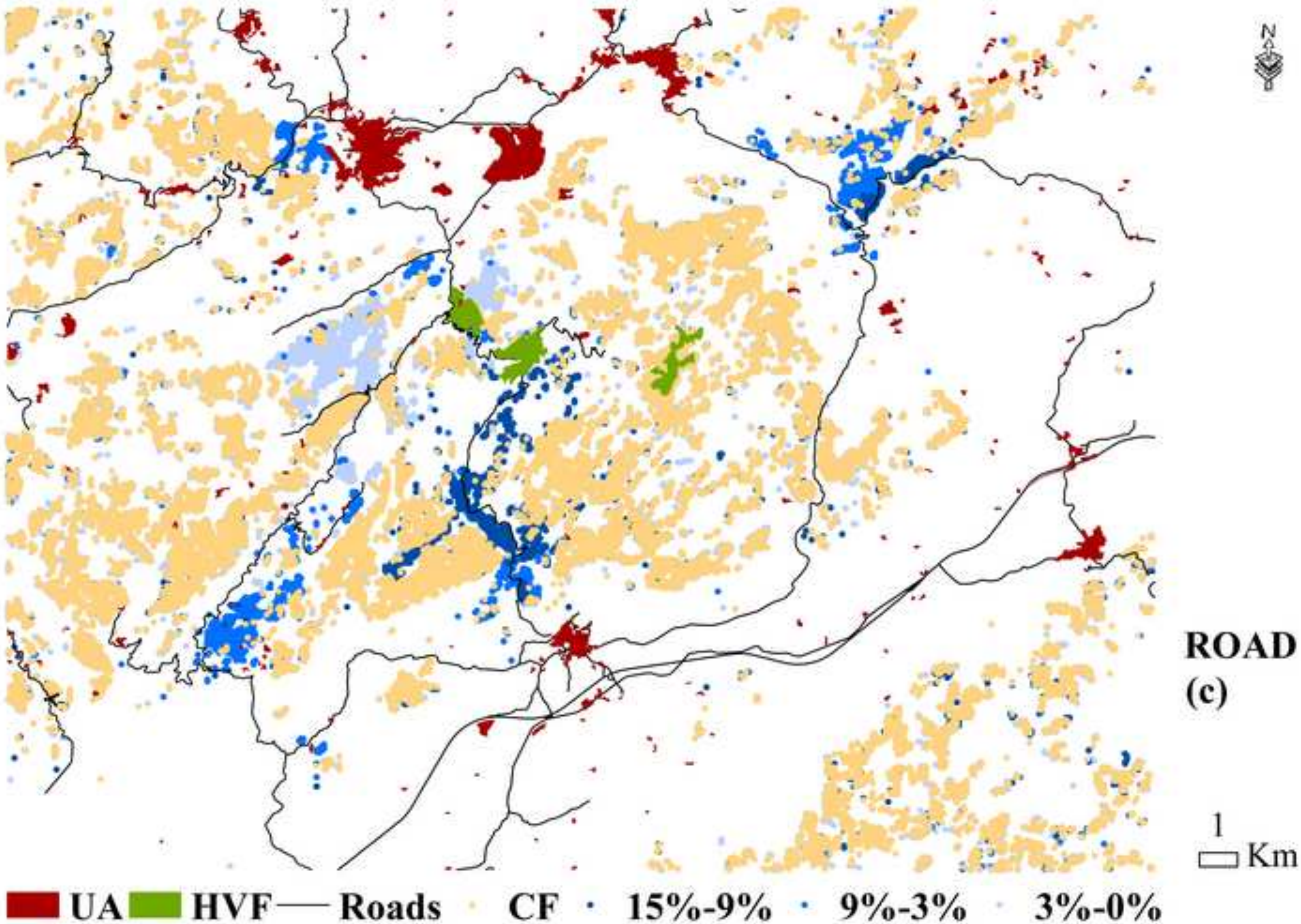

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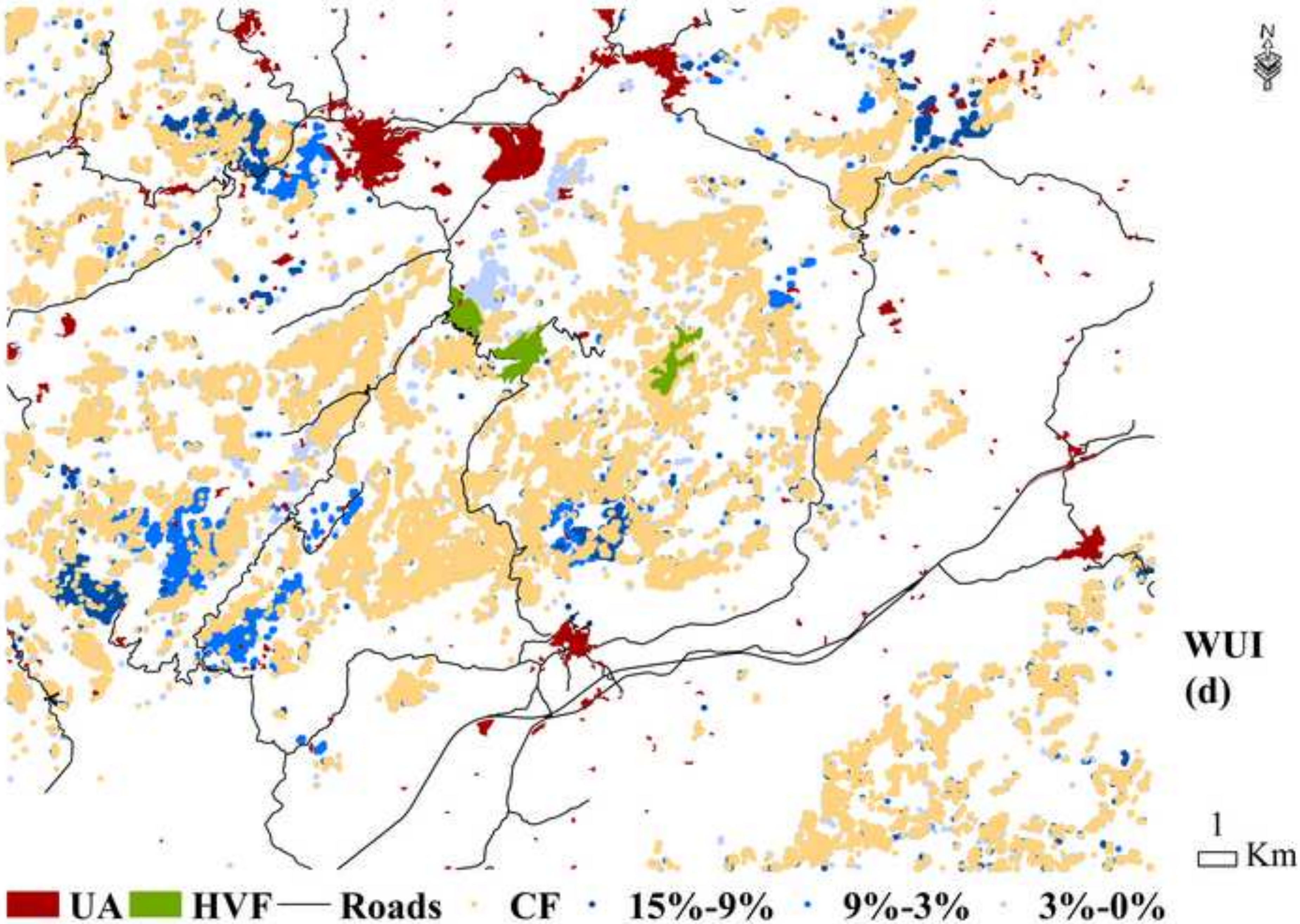


Figure 9

	HECTARES CFL>2.5
T0	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

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

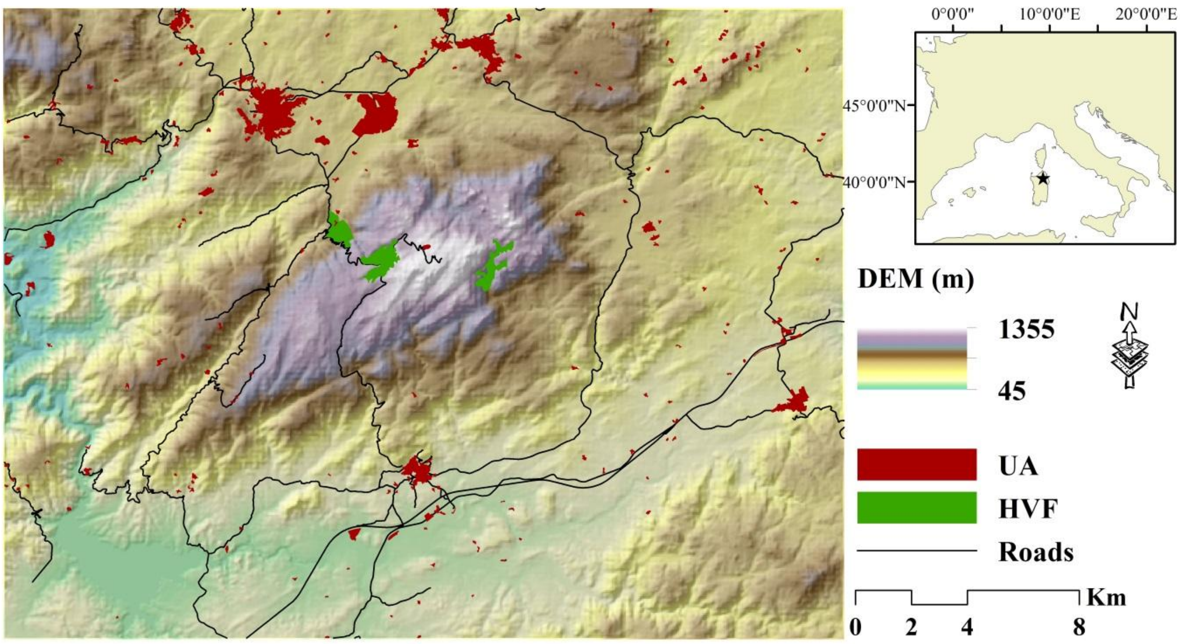


Fig.1. Digital elevation model (DEM) of the study area along with roads, urban and anthropic areas (UA), and highly valued forests (HVF).

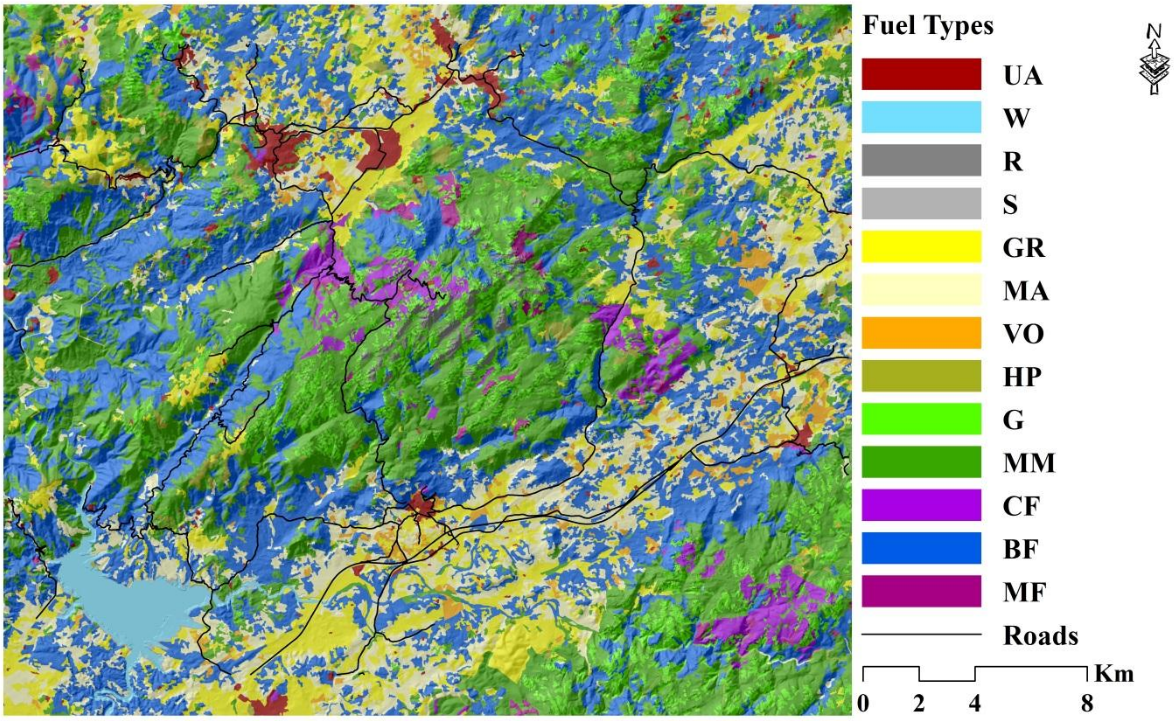


Fig. 2. Main fuel types of the study area. UA=urban and anthropic areas; W=water bodies; R=rocks; S=sands; GR=grasslands; MA=mixed agricultural areas; VO=vineyards and orchards; HP=herbaceous pastures; G=garrigue; MM=Mediterranean maquis; CF=conifer forests; BF=broadleaf forests; MF= mixed forests

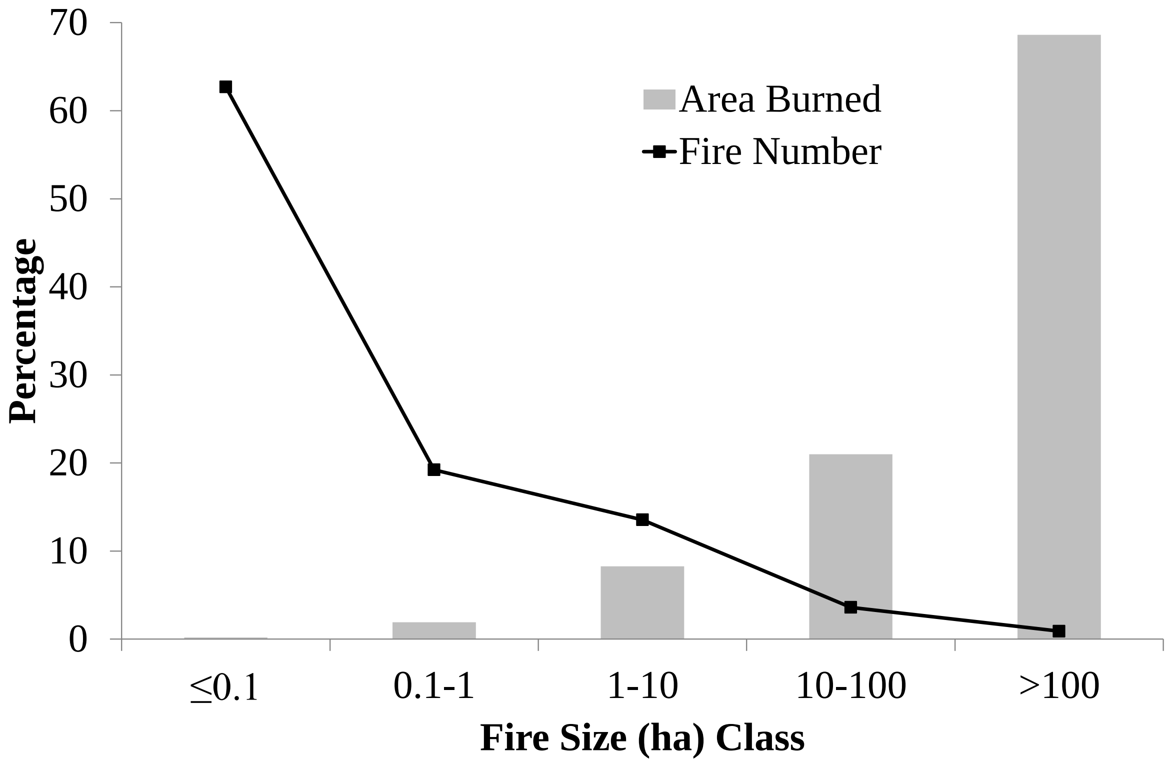


Fig. 3. Percentage of area burned and fire number per fire size class in the study area (Sardinia Forest Service, data from 1980 to 2010)

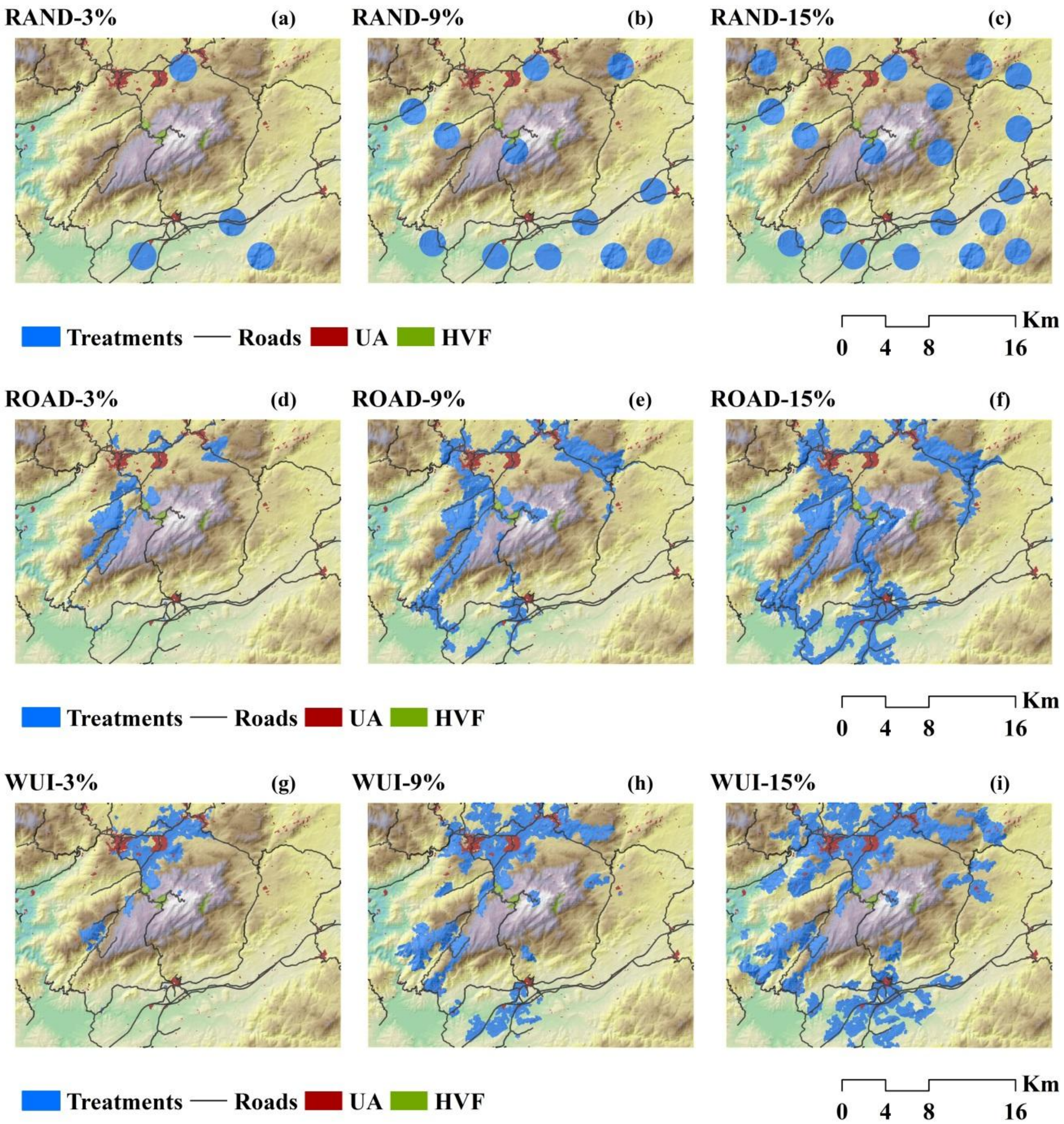


Fig. 4. Maps of the fuel treatment strategies tested (random treatments (RAND, a, b, c), road protection (ROAD, d, f, g), urban and anthropic areas protection (WUI, g, h, i)), considering 3%, 9% and 15% of the landscape treated.

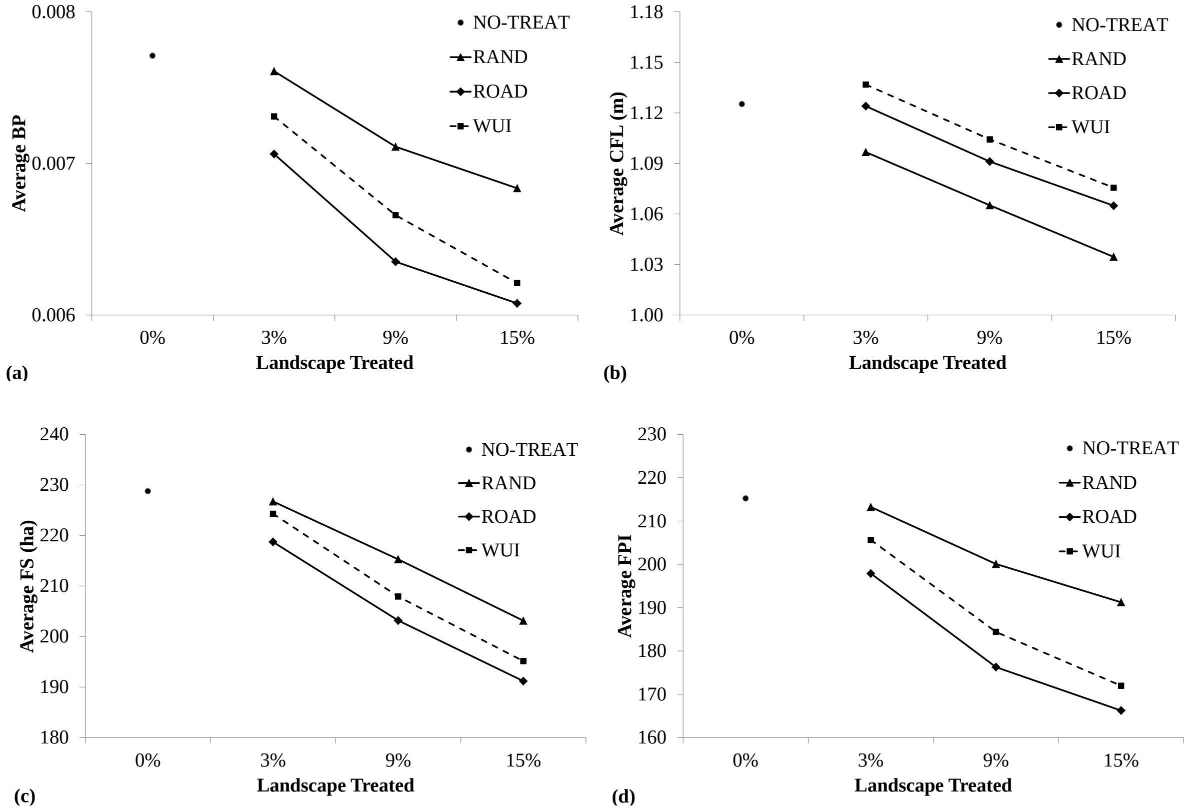


Fig. 5. Effect of fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI) and treatment intensity (3%, 9%, 15%) on average burn probability (BP, a), conditional flame length (CFL, b), fire size (FS, c) and fire potential index (FPI, d). This analysis was performed considering the whole landscape.

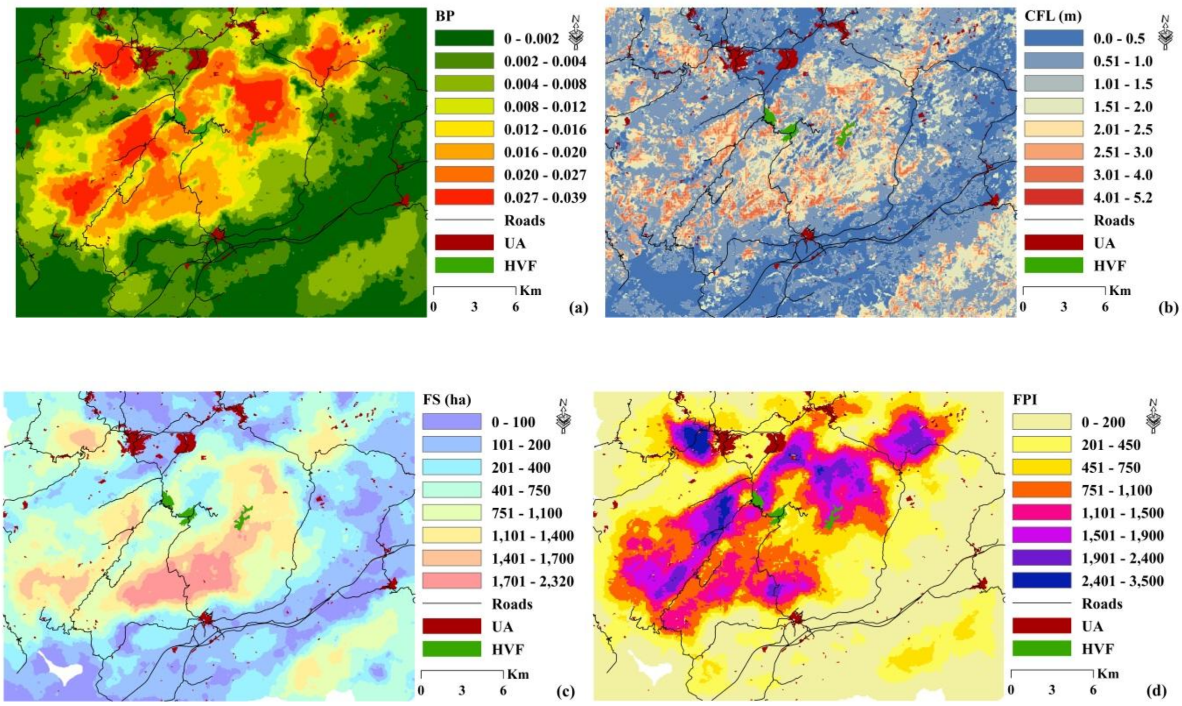
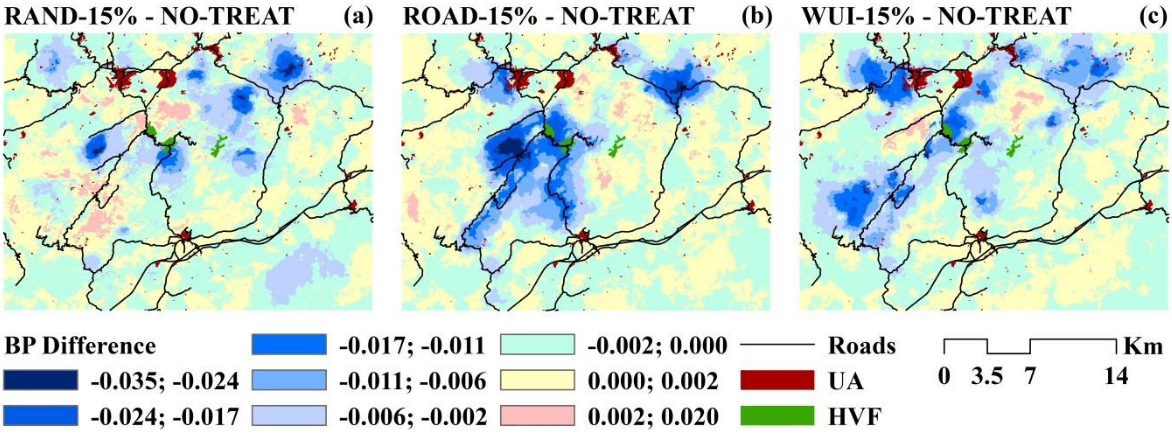
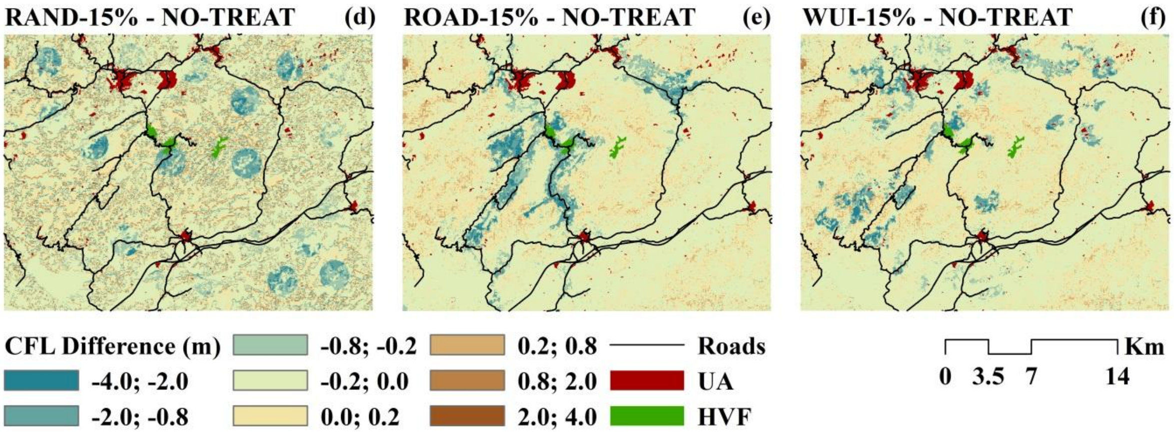


Fig. 6. Burn probability (BP, a), conditional flame length (CFL, b), fire size (FS, c), and fire potential index (FPI, d) for the untreated scenario (NO-TREAT).


RAND-15% - NO-TREAT (a)
ROAD-15% - NO-TREAT (b)
WUI-15% - NO-TREAT (c)
BP Difference
-0.035; -0.024
-0.024; -0.017
-0.017; -0.011
-0.011; -0.006
-0.006; -0.002
-0.002; 0.000
0.000; 0.002
0.002; 0.020
Roads
UA
HVF
0 3.5 7 14 Km


RAND-15% - NO-TREAT (d)
ROAD-15% - NO-TREAT (e)
WUI-15% - NO-TREAT (f)
CFL Difference (m)
-4.0; -2.0
-2.0; -0.8
-0.8; -0.2
-0.2; 0.0
0.0; 0.2
0.2; 0.8
0.8; 2.0
2.0; 4.0
Roads
UA
HVF
0 3.5 7 14 Km

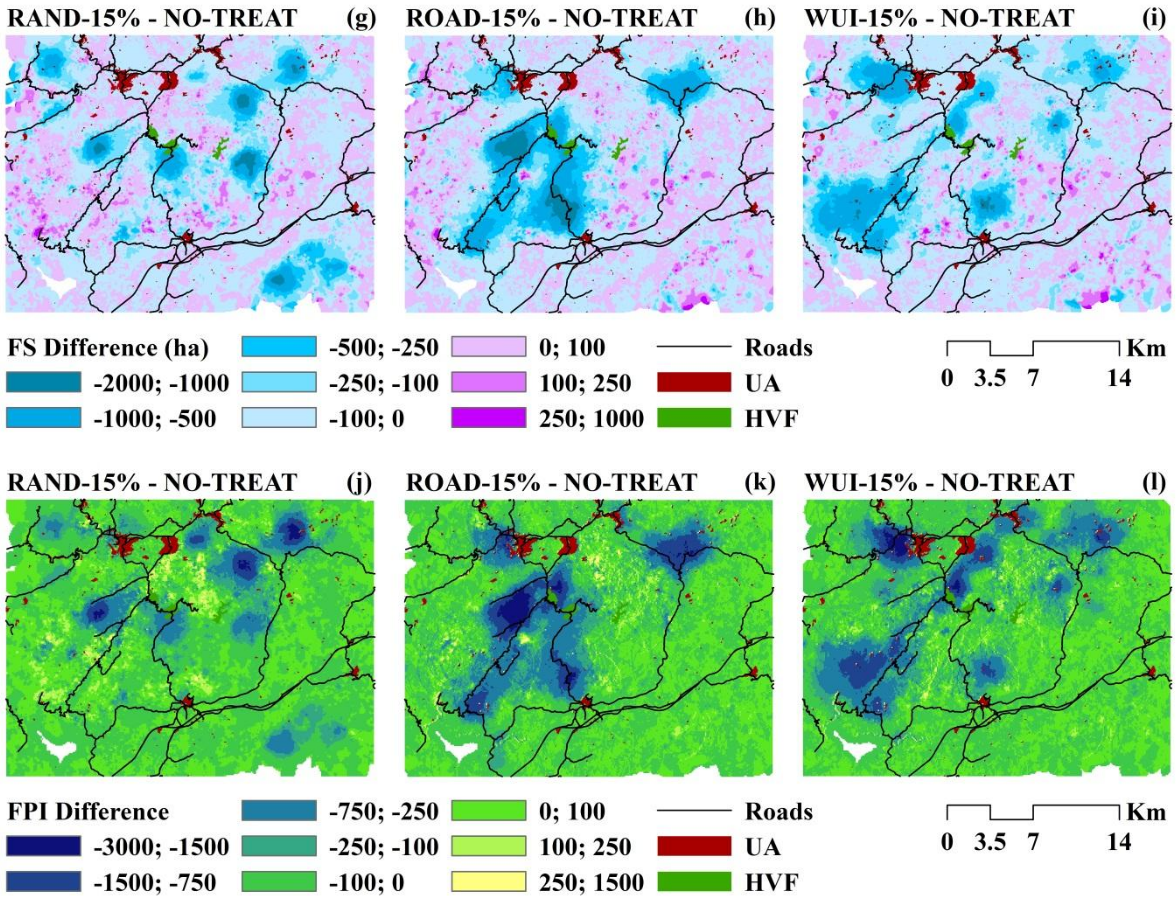


Fig. 7. Differences in BP (a, b, c), CFL (d, e, f), FS (g, h, i) and FPI (j, k, l) between the fuel treatment strategies (RAND, ROAD and WUI, considering the treatment intensity of 15%) and the untreated condition (NO-TREAT).

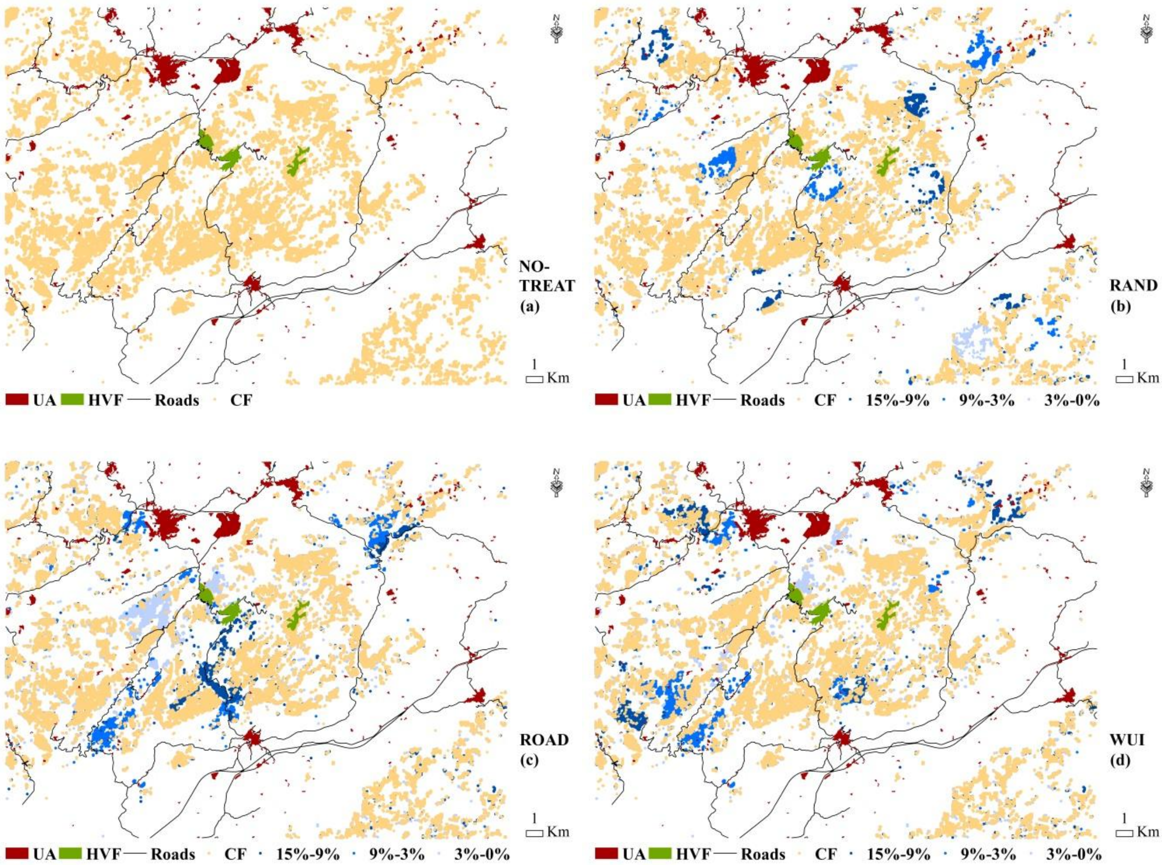


Fig. 8. Potential crown fire (CF) occurrence considering the diverse strategies (NO-TREAT, a; RAND, b; ROAD, c; WUI, d). The areas with different blue color gradations, from light to dark, indicate the reduction of crown fires associated with increasing treatment intensities (3%, 9%, 15% of the landscape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

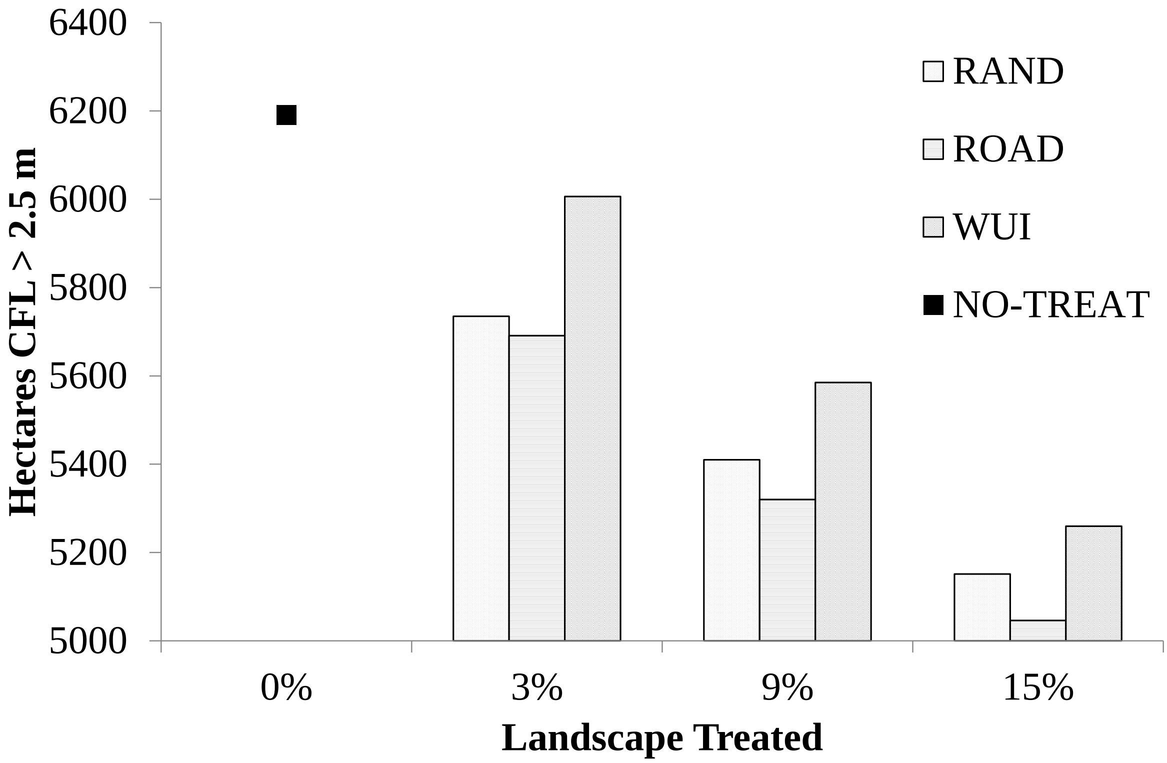


Fig. 9. Effect of fuel treatment strategies (NO-TREAT, RAND, ROAD, WUI) and treatment intensities on the number of hectares with CFL values above 2.5 m.

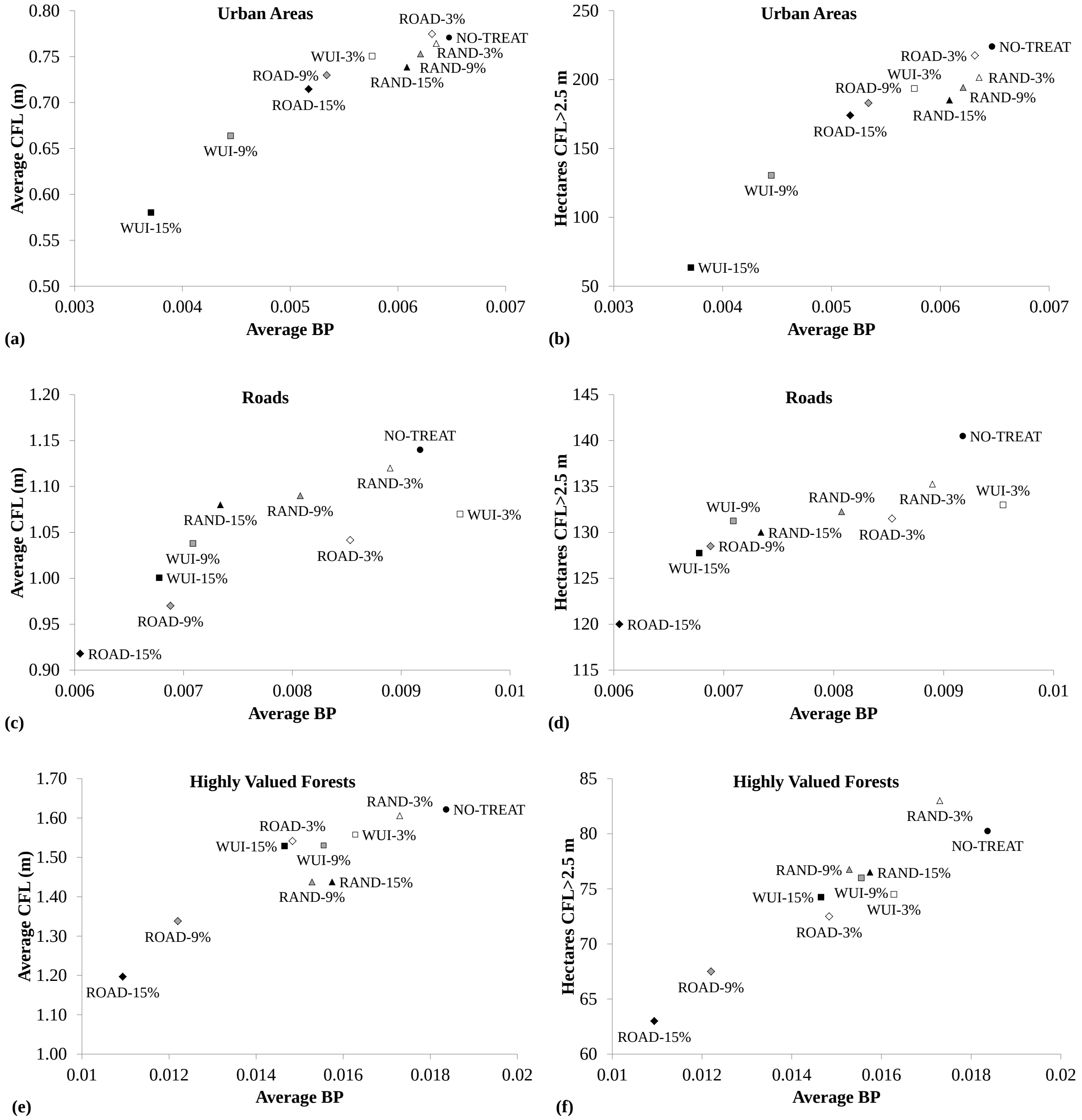
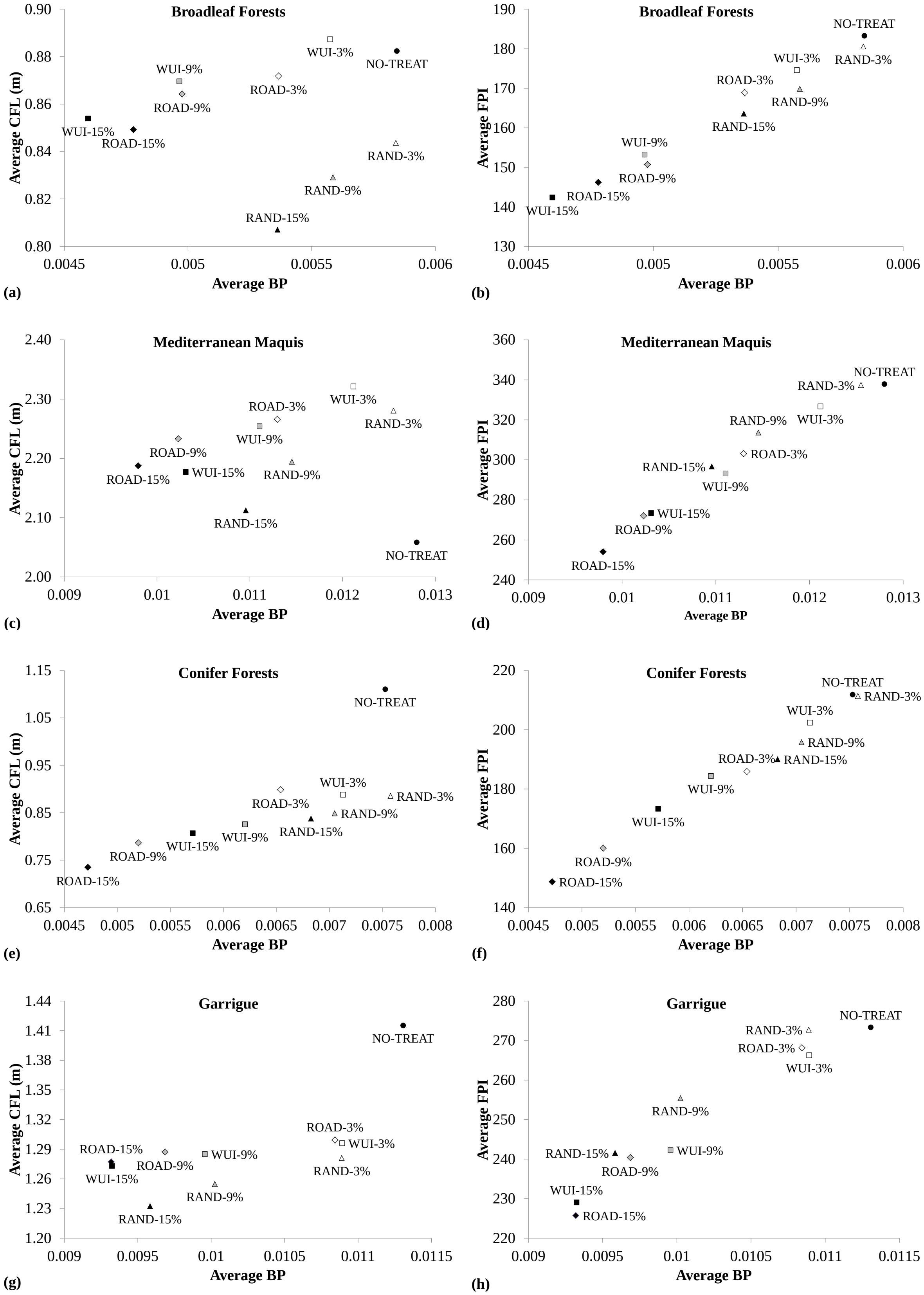


Fig. 10. Scatterplots of BP vs. CFL and BP vs. hectares with CFL>2.5 m in the surroundings (buffer 150 m) of urban areas (a, b), roads (c, d), and highly valued forests (e, f).


Broadleaf Forests
Average CFL (m)
Average BP
NO-TREAT
WUI-3%
ROAD-3%
RAND-3%
WUI-9%
ROAD-9%
RAND-9%
WUI-15%
ROAD-15%
RAND-15%
(a)
Broadleaf Forests
Average FPI
Average BP
(b)
Mediterranean Maquis
Average CFL (m)
Average BP
(c)
Mediterranean Maquis
Average FPI
Average BP
(d)
Conifer Forests
Average CFL (m)
Average BP
(e)
Conifer Forests
Average FPI
Average BP
(f)
Garrigue
Average CFL (m)
Average BP
(g)
Garrigue
Average FPI
Average BP
(h)

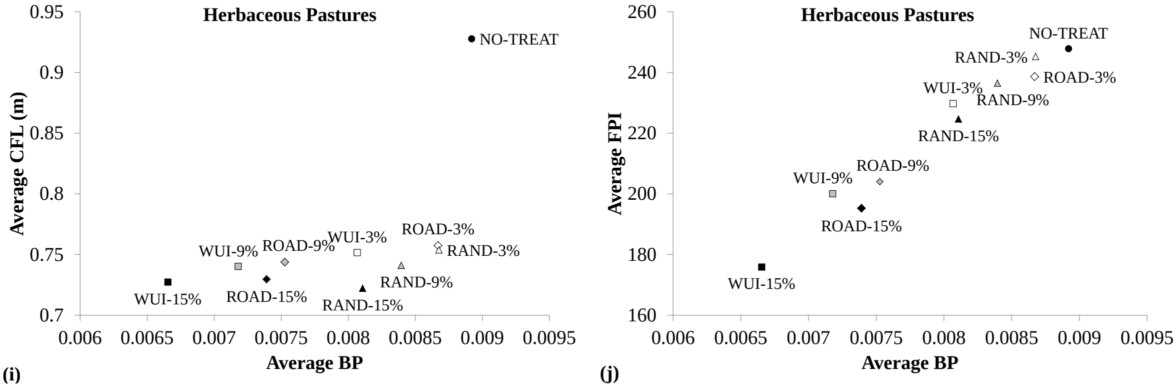


Fig. 11. Scatterplots of average BP vs average CFL (left) and average BP vs average FPI (right) for the main vegetation types (broadleaf forests, a, b; Mediterranean maquis, c, d; conifer forests, e, f; garrigue, g, h; herbaceous pastures, i, j) of the study area, considering all the fuel treatment strategies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