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Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area

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Abstract

Wildfire spread and behavior can be limited by fuel treatments, even if their effects can vary according to a number of factors including type, intensity, extension, and spatial arrangement. In this work, we simulated the response of key wildfire exposure metrics to variations in the percentage of treated area, treatment units size, and spatial arrangements of fuel treatments under different wind intensities. The study was carried out in a fire-prone 625 km^2 agro-pastoral area mostly covered by herbaceous fuels, and located in Northern Sardinia, Italy. We constrained the selection of fuel treatment units to areas covered by specific herbaceous land use classes and low terrain slope (< 10%). We hypothesized to treat 2%, 5% and 8% of the landscape area, and we identified priority sites to locate the fuel treatments units for all treatment alternatives. The fuel treatment alternatives designed diverse mosaics of disconnected treatment units with different size (0.5-10 ha, LOW strategy; 10-25 ha, MED strategy; 25-50 ha, LAR strategy); in addition, treatment units in a 100 m buffer around the road network (ROAD strategy) were tested. We assessed pre- and post-treatment wildfire behavior by the Minimum Travel Time (MTT) fire spread algorithm. The simulations replicated a set of south-western wind speed scenarios (16, 24 and 32 km h^{-1}) and the driest fuel moisture conditions observed in the study area. Our results evidenced that the fuel treatments performed nearby the existing road network were significantly more efficient than the other alternatives, and this difference was amplified at the highest wind speed. Moreover, the largest size treatment units were the most effective in containing wildfire growth. As expected, increasing the percentage of landscape treated and reducing wind speed lowered fire exposure profiles for all fuel treatment alternatives, and this was observed for both landscape scale and highly value resources. The methodology presented in this study can support the design and optimization of fuel management programs and policies in agro-pastoral areas of the Mediterranean Basin and herbaceous type landscapes elsewhere, where recurrent grassland fires pose relevant threat to rural communities, farms and infrastructures.

Keywords

Fuel treatments; burn probability; MTT algorithm; Mediterranean areas; fire management; fire risk

1. Introduction

The occurrence of large wildfire events is mainly associated with extreme weather conditions and the presence of highly flammable, unmanaged and continuous forest fuels (Cardil *et al.*, 2017; Dimitrakopoulos *et al.*, 2011; Fernandes *et al.*, 2012; Keeley *et al.*, 2012; Pausas and Vallejo, 1999; San-Miguel Ayanz *et al.*, 2013; Xanthopoulos *et al.*, 2009). Nonetheless, in the Mediterranean Basin, wildfires often affect areas largely characterized by the presence of herbaceous flashy fuels, such as open woodlands (e.g.: *dehesas* and *montados*), meadows and pastures, or dryland crops (e.g.: wheat, barley, and oat) (Bajocco *et al.*, 2017; Levin *et al.*, 2016; Naveh, 1973; Salis *et al.*, 2014). In these areas, the presence of cured herbaceous fuels during the whole fire season favors the ignition and propagation of large wildfires, even with moderate weather and low fuel loads, as well as the ignition of short-distance spot fires in advance of the main fire front, which further enlarges fire perimeters and complicates fire suppression efforts (Colin *et al.*, 2002; Costa-Alcubierre *et al.*, 2011; Nudda *et al.* 2015, 2016, 2017; Salis *et al.*, 2016*a*). Furthermore, in several Mediterranean areas herbaceous fuels are preferential sites of fire ignitions, and thus can be a source of large events that can later spread into forests or anthropic values (Alcasena *et al.*, 2017; Gonzalez-Olabarria *et al.*, 2015; Ricotta and Di Vito, 2014). For instance, the largest event that affected the island of Sardinia (Italy) in the last 20 years (Bonorva wildfire, July 2009, 10,600 ha burned), one of the largest wildfire events ever occurred in Italy, mainly affected herbaceous-type land tenures (Salis *et al.*, 2012; Schmuck *et al.*, 2010). This wildfire spread for two days under extreme weather conditions, presented maximum spread rates close to 4 km h^{-1}, and caused substantial losses to agro-pastoral farms and inland rural communities (Fois, 2015): moreover, even aerial resources had limited success in containing the wildfire spread.

Wildfire management within the Mediterranean Basin continues to increase in complexity, due to a number of converging drivers that amplify potential threats to ecological, social and economic values (Bovio *et al.*, 2017; Corona *et al.*, 2015; Curt and Frejaville, 2017; Moreira *et al.*, 2011; Salis *et al.*, 2016*b*). Major drivers include the increasing presence of anthropic values and activities into fire-prone areas, the budget constraints in promoting wildfire prevention and mitigation policies, the progressive ageing of population and land abandonment in forest and rural areas, the lack of adequate fuel management, and climate change (Bedia *et al.*, 2014; Bonet and Pausas, 2007; Brotons *et al.*, 2013; Chergui *et al.*, 2017; Curt *et al.*, 2013; EEA, 2017; Fernandes, 2013; Karali *et al.*, 2013; Lozano *et al.*, 2017; Madrigal *et al.*, 2017; Oliveira *et al.*, 2017; Pausas and Fernandez-Munoz, 2012; Pellizzaro *et al.*, 2012; Ruiz-Mirazo *et al.*, 2012; Salis *et al.*, 2014; Turco *et al.*, 2015; Velez, 2002; Xanthopoulos *et al.*, 2006). Consequently, there is a growing interest towards wildfire risk assessment tools that can support land managers and policy makers in mapping wildfire exposure, prioritizing fuel treatment efforts, developing comprehensive strategies for risk mitigation and climate change adaptation, and optimizing strategies and investments with finite budgets while accounting for diverse operational constraints (Ager *et al.,* 2011, 2017; EEA, 2017; Piqué-Nicolau *et al.*, 2014; Thompson *et al.,* 2012, 2013). To induce relevant changes in fire spread and behavior, it is widely accepted that the most efficient approach is represented by the alteration of fuel conditions (e.g.: load and continuity) at landscape scale (Agee and Skinner, 2005; Reinhardt *et al.,* 2008). Fuel management is primarily intended to modify wildfire behavior and growth through strategic placement and arrangement of treatments units on strategic locations (Ager *et al.,* 2010, 2013; Cochrane *et al.* 2012; Finney, 2001; Graham *et al.,* 2004; Liu *et al.* 2013; Oliveira *et al.*, 2016; Parisien *et al.* 2007; Salis *et al.*, 2016*b*; Schmidt *et al.,* 2008). Moreover, treating fuels can help fire crews to suppress wildfires by enlarging safety areas or escaping routes, and hence can enhance their potential to contain an event (Agee *et al.*, 2000; Calkin *et al.*, 2014; Montiel and Kraus, 2010; Weatherspoon and Skinner, 1996).

The integration of fuel management strategies into wildfire management poses a number of tradeoffs for land managers that need to identify the best spatial arrangements and treatment solutions while taking into account management goals, and financial, social, legal and physical constraints (Agee and Skinner, 2005; Ager *et al.*, 2010, 2013, 2017; Arganaraz *et al.*, 2017; Collins *et al.* 2010; Corona *et al.*, 2015; Finney *et al.,* 2007; Hand *et al.*, 2014; Hudak *et al.,* 2011; O'Connor *et al.*, 2016; Parsons *et al.,* 2017; Reinhardt *et al.*, 2008; Schmidt *et al.,* 2008; Scott *et al.,* 2016; Thompson *et al.*, 2012, 2017; Thompson and Calkin, 2011; Vogler *et al.*, 2015). Overall, fuel treatments will not stop or eliminate fires (Calkin *et al.,* 2014; Finney and Cohen, 2003; Price and Bradstock, 2010): in fact, scattered widespread fuel treatments can be by-passed or eluded by large events (Finney, 2004, 2007; Reinhardt *et al.,* 2008). Yet, fuel treatments and land management strategies are supported by relatively little research, particularly in the Mediterranean Basin context, on how the treatment strategies and the spatial arrangements of treated units affect wildfire transmission and behavior, and on the effectiveness of fuel treatments to limit wildfire growth and exposure at landscape scale (Alcasena *et al.,* 2017; Duguy *et al.,* 2007; Fernandes *et al.,* 2004; Gonzalez-Olabarria and Pukkala, 2011; Mitsopoulos *et al.,* 2016; Oliveira *et al.,* 2016; Salis *et al.,* 2016*b*). Preliminary works evidenced that the maximum efficiency in fuel treatment effectiveness while minimizing the area treated could be obtained by the creation of patterns of rectangular treatment units, and regular mosaic patterns were proved to be more efficient than random arrangements, particularly when small surfaces are treated (Bevers *et al.,* 2004; Finney, 2001, 2004; Loehle, 2004; Schmidt *et al.,* 2008). Promising results have been obtained by the development of fuel treatment optimization models, which would mitigate fire risk while taking into account fuel management multi-objective perspectives or specific needs (Ager *et al.,* 2013; Alcasena *et al.*, 2018; Arca *et al.,* 2015; Chung *et al.,* 2013; Finney, 2007; Kennedy *et al.,* 2008; Rytwinski and Crowe*,* 2010; Vogler *et al.,* 2015). The final evaluation of the effectiveness of fuel treatments typically requires the estimation of altered wildfire spread and behavior after and before the fuel treatment strategies (Ager *et al.,* 2010, 2014; Finney *et al.,* 2007; Kim *et al.,* 2009; Schmidt *et al.,* 2008; Stratton, 2004). In recent years, spatial fire growth simulators and burn probability modeling approaches based on the MTT algorithm (Finney, 2002) have emerged as useful tools for analyzing the influence of fuel treatments on wildfire growth and behavior, and for performing risk-based simulation of fuel treatment efficiency. (Finney, 2005, 2007; Miller *et al.,* 2008; Riley and Thompson, 2017; Thompson *et al.,* 2012).

The goals of this study were to (1) analyze the effects of different fuel treatment arrangements, treatment unit size, and percentages of treated area on simulated wildfire exposure metrics at landscape scale, and (2) determine to what extent the treatment effectiveness is conditioned by diverse wind speed conditions. With this purpose, we simulated fire spread and behavior considering the driest fuel moisture conditions in a study area of about 625 km^2, mainly covered by herbaceous surface fuels, and located in Northern Sardinia, Italy. Fuel treatments were constrained to specific herbaceous land use classes and converted the treated units into unburnable areas. The methodology and findings presented in this study can support the design and optimization of fuel management programs and wildfire risk mitigation policies in agro-pastoral areas of the Mediterranean Basin.

2. Material and Methods

2.1 Study area

The study area is located in Northern Sardinia, Italy, and has nearly 62,500 ha of land (Fig. 1). Overall, the area is characterized by the presence of large flat zones, with the highest peaks (Goceano mountains) located in the south-eastern portion of the territory. The elevation ranges from about 180 m a.s.l. to 970 m a.s.l., with an average elevation of about 400 m a.s.l. (Fig 1). The climate is Mediterranean, with relevant variations in temperatures and precipitations between the hot and dry period and the cold and wet winter. The average annual precipitation is about 650 mm; peaks of more than 750 mm are common at the highest elevations (Chessa and Delitala, 1997). The most relevant precipitations are concentrated in November and December, while July is the hottest and driest month of the year. The average annual temperature is about 13°C; maximum temperatures are often above 30°C in the summer season.

FIG. 1 APPROXIMATELY HERE

The study area is one of the most important agro-pastoral areas of Sardinia. In fact, sheep (about 800 farms and 300,000 heads) and cattle farms (about 450 farms and 15,000 heads) are key components of the productive sector of the area. Moreover, about 1,700 farms (with at least 1 ha of land) are involved in agricultural productions (ISTAT, 2010). The area consists of a number of small municipalities, with about 25,000 residents (ISTAT, 2011); urban and anthropic areas cover approximately 1,400 ha of land (Fig. 1 and Fig. 2). The vegetation is largely characterized (about 65%) by the presence of herbaceous fuels, the most of which is classified as grasslands and pastures (Fig. 2). Herbaceous and open wooded pastures, as well as marginal shrublands and woodlands, play a key role in the economy and needs of the local livestock farms. Grasslands are mainly devoted to herbaceous autumn-winter crop productions. Shrubland formations (8%) are relatively tall and complex in the most of the study area, and comprise *Olea europaea* L. var. oleaster Hoffgg. Et Link, Phyllirea spp., *Pistacia lentiscus* L., low-height Quercus spp.; low brushes (e.g.: Cistus spp., Pyrus spp.; Prunus spp.) are present in the most degraded and grazed lands. Broadleaf forests (17%) are mainly confined to hills and mountain areas (Fig. 2), and are principally constituted by *Quercus pubescens* Willd*.,* *Quercus suber* L*.,* and

Quercus ilex L.. Fruit-bearing areas are represented by sparse and family-farm vineyards, olive groves and cherry-trees, and cover about 2% ha of land, mainly concentrated in the western plains (Fig. 2).

FIG. 2 APPROXIMATELY HERE

2.2 Wildfire data

We used the 1998-2015 fire database provided by the Sardinia Forest Service. This database contains information on ignition point coordinates, municipality, ignition date, and fire size. In the above-period, the study area experienced about 950 fire ignitions (Fig. 1), and the total area burned was close to 19,500 ha, that is on average about 55 wildfires and 1,080 ha of land burned per year. Overall, wildfires above 100 ha accounted for 82% of the total area burned, and only for 1.5% of the total fire number in the study area: these large events were concentrated from late June to late August. Fires were frequently ignited nearby roads, surroundings of villages and small family-conduction farms (Fig. 1). The main wind direction (SW) associated with large wildfires (> 100 ha) in the study area was derived from wildfire reports, weather data, and personal communication of the Sardinia Forest Service. SW winds contributed to about 79% of the total area burned by wildfires > 100 ha in the period 1998-2015. The main weather pattern associated to these large events is related to the movement of hot and dry air masses from North-Africa (which in North-western Sardinia often flow from SW due to orographic effects), originated by a low-pressure cell moving eastward across the western Mediterranean Sea. The most of the total area burned was related to the wildfire of Bonorva (Fig. 1), which was ignited on July 23, 2009, spread for more than 20 km and burned approximately 10,600 ha in about 36 hours. The largest fire area growth was observed in the timeframe 11 a.m. – 7.00 p.m.. The day of the fire was characterized by extreme weather conditions in the whole island of Sardinia, in terms of temperatures, relative humidity and high-intensity winds (ARPAS, 2009).

2.3 Input data for wildfire modeling

We gathered all input data needed to produce a 25 m resolution gridded landscape file for the study area as required by FlamMap (Finney, 2006). The terrain characteristics (elevation, slope and aspect) were derived from 10-m digital elevation data of the island (Sardinia Region geo-portal, 2017). Surface fuels were interpreted from the 2008 Sardinian Land Use Map (Sardinia Region geo-portal, 2017). We associated to the land use classes either a standard or custom surface fuel model (Anderson, 1982; Arca *et al.,* 2009; Salis *et al.*, 2013; Scott and Burgan, 2005) (Fig. 2 and Suppl. Tab. 1). Canopy metrics (canopy cover, canopy bulk density, canopy base height and canopy height) for forest areas were estimated using as reference *Quercus suber* L. and *Quercus pubescens* L. stands, considering the data from the National Inventory of Forests and Forest Carbon Sinks (INFC, 2005) (Suppl. Tab. 1). Fuel moisture content (FMC) for the 1-h and 10-h time lag dead fuel was determined by the data and methods of Pellizzaro *et al.* (2005, 2007) and Salis *et al.* (2015), and focusing above the 97th percentile values. Considering that the most of the study area is flat and that preliminary tests with WindNinja (Forthofer 2007) showed limited variations between constant and simulated wind fields in the fuel treatment areas, fire simulations were performed using constant wind fields. In more detail, wind direction was held constant (225°), while three different wind speed conditions (16, 24 and 32 km h^{-1}) were set as reference. Finally, we selected all fire ignition locations for the period 1998-2015 in the study area and derived a smoothed historic fire ignition density map. The fire ignition density map was held constant for all the fire simulations.

2.4 Fuel treatment alternatives

Overall, we generated 13 fuel treatment alternatives, which consisted of the untreated condition (NO-TREAT) and 12 treatment scenarios obtained by the combination of 3 percentages of landscape treated with 4 different strategies in the spatial selection of the land use units to be treated (Fig. 3). Each fuel treatment alternative originated a specific 25 m x 25 m surface fuel raster map for wildfire simulations (Fig. 3). We imposed specific criteria for the spatial selection of the single land use units to be treated (Tab. 1).

FIG. 3 AND TAB. 1 APPROXIMATELY HERE

Fuel treatments were hypothesized on single land use units classified with the codes 241, 211, and 212 by the 2008 Sardinian Land Use Map (Tab. 1). Only single land units with size between 0.5 and 50 ha were identified as possible targets of the fuel treatments. To avoid potential soil erosion issues in case of heavy rain events after the treatments, we limited the possibility of performing the treatments to areas with terrain slope < 10 degrees. As indicated in Tab. 1, fuel treatments converted the treated units into unburnable areas *sensu* NB models of Scott and Burgan (2005). Fuel treatments were applied to 2% (≈ 1,200 ha), 5% (≈ 3,000 ha), and 8% (≈ 4,800 ha) of the landscape area (Fig. 3). We identified specific priority areas to locate the fuel treatments units for all the strategies tested: these priority areas were held constant for all the strategies taken into account (Tab. 1). Three fuel treatment strategies focused on the design of disconnected single treatment units characterized by different extent: low size (LOW strategy, 0.5-10 ha), medium size (MED strategy, 10-25 ha), or large size (LAR strategy, 25-50 ha) land use units. In addition, we included a fourth fuel treatment alternative which consisted in the selection of treatment units in a 50 m buffer around the road network (ROAD strategy).

2.5 Spatial data on selected anthropic values

We obtained spatial data on selected anthropic values of the study area from the Sardinia Land Use Map (2008). The selected features consisted of continuous urban fabric (CUF, ≈ 445 ha), discontinuous urban fabric (DUF ≈ 490 ha), industrial and commercial units (ICU, ≈ 280 ha), and sport and green urban areas (SGU, ≈ 111 ha), and covered about 1,325 ha of the study area. In order to measure simulated wildfire metrics around the above values, we considered a reference zone that consisted of a 150-m buffer surrounding the individual polygons. This distance was adequate to capture the general fire behavior in the vicinity of the values, and to focus on the most important human features of the community. Overall, the buffer areas used to investigate wildfire behavior around the selected anthropic values was close to 7,900 ha, the most of which (5,300 ha) related to DUF values. Simulated burn probability and flame length values were used as key wildfire exposure metrics to characterize respectively the probability that a wildfire could affect the vicinity of a given anthropic value, and the potential average intensity at which the wildfire would burn each buffer pixel.

2.6 Wildfire simulation modeling

The wildfire simulations were performed using the minimum travel time (MTT) spread algorithm of Finney (2002), as implemented in Randig. The MTT algorithm has been widely used and is routinely applied to fire management problems, at a broad range of scales and with multiple purposes (Miller and Ager, 2013; Salis *et al.,* 2013). The MTT algorithm models two-dimensional fire growth under constant weather following the Huygens' principle, where fire edge growth and behavior are modeled as a vector or wave front (Finney, 2002; Knight and Coleman, 1993; Richards, 1990). Randig calculates surface fire spread according to the Rothermel's equation (1972); crown fire initiation and spread are calculated according to Van Wagner, 1977. and Rothermel, 1991, respectively. We simulated 5,000 wildfires for each fuel treatment alternative. The ignitions points were located within the burnable fuels of the study area, according to the ignition probability grid originated from the historical fire database. Simulations were performed at 25 m resolution, consistent with the input data, with constant fuel moisture and wind direction (225°), and a burning period of 8 hours, which reflected the major fire growth duration of the Bonorva wildfire. Three different wind intensities (16, 24 and 32 km h^{-1}) were set as reference and were used as input for the wildfire spread modeling. Regarding spot fires, in preliminary works we found that spotting probabilities in the range 1-2% was the best compromise to accurately model large fire events in Sardinia in conditions of intense winds (Alcasena *et al.*, 2015, Salis *et al.*, 2013, 2016). In this study, we used a spot probability of 1% as reference for each fire simulation due to the fact that the study area is largely covered by herbaceous fuels, which typically have lower potential to originate embers than forests or shrublands. Suppression activities were not taken into account by the simulation exercise. The wildfire simulations generated a conditional burn probability (BP) as well as a frequency distribution of flame lengths (FL) in 0.5 m classes at each pixel of the study area. The conditional burn probability is the chance that a pixel will burn at a specific flame length interval, given an ignition in the study area. From the frequency distribution of FL values at each pixel we derived the weighted flame length, which is the conditional flame length (CFL). We then calculated the potential fire size (FS) grid, which was obtained by smoothing the fire size output using the inverse distance weighting (search distance 1,000 m) of

ArcMap. Burn probability, flame length and fire size were used as indicators to analyze the wildfire response to variations in percentage of landscape treated, wind speed and spatial arrangements of fuel treatments. We considered 2.5 m as flame length threshold to identify the areas where fire intensity can potentially overwhelm ground crew fire suppression capabilities (Andrews *et al.,* 2011). Statistical differences between fuel treatments and the NO-TREAT control was carried out by the Wilcoxon signed rank test. Significance of difference was evaluated using a *p*-value level of 0.05.

3. Results

3.1 Wildfire exposure at landscape scale

3.1.1 Burn probability. On a pixel basis, landscape burn probability (BP) ranged from a low of 0 to a maximum of 0.1606 for the NO-TREAT condition and the highest wind speed value (Tab. 2 and Fig. 4). Burn probability in all fuel treatment alternatives, including the NO-TREAT condition, was strongly influenced by wind speed. In fact, increments in wind speed promoted growth in average BP values, which for the NO-TREAT condition increased from 0.0136 (16 km h^{-1}) to 0.0284 (24 km h^{-1}) up to 0.0442 (32 km h^{-1}) (Tab. 2 and 3).

FIG. 4, TAB. 2 AND TAB. 3 APPROXIMATELY HERE

Regardless spatial arrangements, wind speeds and percentages of area treated, the statistical test revealed significance of BP variations due to treatment strategies. The Wilcoxon test identified significant differences between the control and all treatment strategies, in particular when the 5% and 8% of landscape was treated, regardless the type of treatment and the wind speed scenario. Regarding the road strategy, significant differences were also obtained with 2% of the landscape treated, regardless to the wind scenario. Average BP decreased following a non-linear trend with increasing percentages of landscape treated (Tab. 2). For instance, at the highest values of wind speed and for the ROAD strategy, average BP dropped from 0.0407 (2% of landscape treated) to 0.0221 (8% of landscape treated). We observed a clear effect of the treatment alternatives on BP: ROAD was unequivocally the most efficient strategy, while for the other three strategies average BP increased moving from large to low size treatment units (Tab. 2 and 3). For instance, we found that treating 5%

of the landscape using the ROAD strategy was more efficient than treating 8% of the study area with the LOW strategy, even at the lowest wind speed conditions. Furthermore, at 32 km h^{-1} wind speed conditions, treating 8% of the landscape using the ROAD strategy can halve BP with respect to the NO-TREAT conditions (Tab. 2 and Fig. 5). BP maps showed a marked spatial variability, depending on the landscape characteristics, the effects of the spatial arrangement of the treatment alternatives, the percentage of landscape treated and the wind speed conditions (Fig. 4 and 5). The areas with the highest values of BP were associated with 1) the major wildfire flow paths obtained from the Randig simulations and 2) the historic fire ignition density. Overall, the differences in average BP containment among alternatives were emphasized by increasing wind speed conditions and treated areas (Fig. 5).

FIG. 5 APPROXIMATELY HERE

3.1.2 Fire size. The highest FS value was about 5,200 hectares and was observed for NO-TREAT condition and the highest wind speed value (Tab. 4 and Fig. 4). As observed for BP outputs, also FS was strongly influenced by percentage of landscape treated, treatment strategy, and wind speed (Tab. 3 and 4). The Wilcoxon test showed that all the differences between treatments and control were significant with the exception of few pairwise comparison at 2% of treated area (Tab. 3). Under NO-TREAT condition wind speed increased the average FS values at landscape scale from 769 ha (16 km h^{-1}) to 1,555 ha (24 km h^{-1}) to 2,326 ha (32 km h^{-1}) (Tab. 4). The treatment strategies tested decreased average FS even at the lowest percentages of area treated. Again, average FS decreased with increasing percentages of landscape treated (Tab. 4), being the ROAD strategy the most efficient one in limiting fire growth. In fact, among the fuel treatment alternatives tested, the spatial arrangements associated to ROAD strategy were able to promote the most relevant reductions in average FS for all wind speed and treatment intensities. For instance, at the highest values of wind speed and 8% of the landscape treated, average FS dropped from 1,879 ha with the LOW strategy to 1,193 ha with the ROAD strategy. In addition, at the highest wind speed value, ROAD strategy guaranteed a reduction of average FS values compared to NO-TREAT condition close to 10%, 25% and even 50% for treatment intensities of 2%, 5% and 8%, respectively (Tab. 4). At the lowest wind speed, treating 8%

of the area with the ROAD strategy allowed decreasing of about 60% the number of large fires (>1000 ha) with respect to NO-TREAT. As observed for BP, we also found that for all scenarios tested average FS values decreased moving from low to large size treatment unit alternatives (Tab. 4). The maps of the differences in FS between the whole set of fuel treatment alternatives and NO-TREAT conditions for the study area are presented in Fig. 6.

FIG. 6 AND TAB. 4 APPROXIMATELY HERE

3.1.3 Conditional flame length. As far as CFL is concerned, the effects of fuel treatment alternatives in reducing flame length at landscape scale compared to the control condition were much more limited than those observed for BP and FS (Tab. 3 and 5). Overall, treating 2% of the landscape did not produce significant differences between NO-TREAT and the diverse strategies, while 5% and 8% of area treated produced always significant differences with respect to NO-TREAT. The highest average CFL values were in general showed by the NO-TREAT condition, whose average values ranged from 1.28 m (16 km h^{-1}) to 1.58 m (32 km h^{-1}) (Tab. 5). Moreover, for the NO-TREAT conditions, the surface area with CFL above 2.5 m increased respectively of about 12% and 20% moving from 16 to 24 and to 32 km h^{-1} wind speed. All the treatment alternatives tested slightly decreased average CFL with respect to NO-TREAT. Average CFL decreased with growing percentages of landscape treated and moving from the highest to the lowest wind intensities, as expected (Tab. 5). The ROAD strategy was the most efficient spatial arrangement of fuel treatment units in reducing fire intensity, even if the differences at the landscape scale with the other treatments were quite small. For instance, at the highest values of wind speed and 8% of the landscape treated, average CFL moved from 1.49 m (LOW strategy) to 1.42 m (ROAD strategy). The highest CFL values were observed in the south-western zone of the study area, in correspondence to forests and shrublands and complex topography (Fig. 6). The maps of the differences between fuel treatments alternatives and NO-TREAT conditions are presented in Fig. 7.

FIG. 7 AND TAB. 5 APPROXIMATELY HERE

3.2 Wildfire exposure at anthropic values scale

Scatterplots of average BP vs. CFL, and FS levels, for the buffer areas of the selected anthropic features showed considerable variations of the exposure factors among and within features in terms of magnitude and spatial patterns depending on fuel treatment alternative, area treated, and wind speed (Fig. 8).

FIG. 8 APPROXIMATELY HERE

Overall, the fuel treatment strategies that focused on treating nearby roads (ROAD) were highly efficient in protecting the vicinity of the selected anthropic values, while the LOW strategy was often the less efficient one (Fig. 8). In some cases, the ROAD strategy used over 5% of the study area was even more efficient in reducing BP and FS than the other strategies applied to 8% of the landscape, and this effect was particularly frequent at the highest wind speed. On the whole, as observed at landscape scale, only ROAD treatments when applied to 8% of the study area clearly maximized the reduction in exposure factors in the proximity of all the selected WUI values. Also at anthropic values scale, the increase in the area treated induced significant benefits by dropping the average BP and FS. In addition, as expected, the shift from 16 to 32 km h^{-1} wind speed caused relevant positive variations in the fire exposure factors. In fact, for all fuel treatment alternatives, burn probability, flame length and fire size showed the highest values under the most intense winds. Only in a few cases, and only at the lowest wind speed conditions and percentages of area treated, the protection of the areas nearby the anthropic values was not enhanced by the fuel treatment alternatives in terms of BP and FS compared to NO-TREAT (Fig. 8). Focusing on the selected anthropic values, we found that continuous urban fabrics (CUF) were the most exposed WUI category in terms of average CFL and FS for all the scenarios analyzed, as well as for the most of simulations when considering average BP. On the contrary, industrial and commercial units (ICU) and discontinuous urban fabrics (DUF) evidenced the lowest values of CFL and of BP, respectively, for almost all scenarios tested. Due to the high presence of herbaceous fuels in the study area and the type of treatments performed, the effects of wind speed, area treated and spatial arrangements of fuel treatments on BP and FS were more evident than those on CFL. For instance, considering the NO-TREAT scenario, average BP for the selected anthropic values ranged from a low of 0.0147 for DUF with 16 km h^{-1} wind speed to a maximum of 0.0544 for SGU with 32 km h^{-1} wind speed conditions. As far as CFL is concerned, focusing on the NO-TREAT scenario, the values ranged from 1.04 m for ICU with 16 km h^{-1} wind speed to 1.49 m for CUF with 32 km h^{-1} wind speed.

4. Discussion

In this study, we performed fire spread simulations based on the MTT algorithm to test the response of wildfire exposure variables (namely burn probability, flame length and fire size) to variations in percentage of area treated and spatial arrangements of fuel treatments in a fire-prone Mediterranean area. The study area has large portions of land covered by herbaceous surface fuels, mainly related to agricultural (autumn-winter crop productions) and pastoral uses for animal feed (herbaceous and open wooded pastures, as well as degraded shrublands), and for these reasons represents a relevant example of dry Mediterranean agro-pastoral landscapes.

We found that the spatial arrangements based on the strategic fuel treatments designed nearby roads were the most effective in limiting fire growth for all wind speed conditions and percentages of area treated. Similar findings were obtained in a previous work conducted in a Mediterranean landscape (Northern Sardinia, Italy) mainly covered by oak forests and shrublands (Salis *et al.,* 2016*b*). However, the use of a low spotting probability (1%) in our study could have increased the effectiveness of continuous fuel treatments nearby roads vs. the other patchy arrangements. Linear fuel break networks have also been suggested to be more efficient and cost-effective than dispersed fuel treatments by Fernandes *et al.,* 2012 and Oliveira *et al.,* 2016. On the whole, this opens many options for roads being used as preferential fire control lines when the road network sufficiently covers a given landscape (Eastaugh and Molina, 2012; Gill, 2008; Price and Bradstock, 2010), even considering that road networks can limit fire spread both through creation of fuel breaks and by favoring placement of fire management resources (Narayanaraj and Wimberly 2011). The fact that the ROAD treatment strategy was the most effective solution to mitigate fire size and propagation could strengthen the guidelines of the regional fire regulations and planning (Sardinia Regional

Government, 2017), which imposes fuel management in the vicinity of the road network as general wildfire prevention activity. On the other hand, to achieve significant results, it would be more appropriate to extend to larger areas (e.g.: 100-m buffers) the treated bands nearby roads, and this would be crucial especially in strategic locations or hot-spot areas (Ager *et al.,* 2013; Eastaugh and Molina, 2012; O'Connor *et al.*, 2017; Oliveira *et al.*, 2016). Plus, managing fuels around roads enhances the prevention of arson and accidental fire ignitions (e.g.: cigarettes), largely increases the potential of roads to act as barriers even in case of spotting, can make firefighting operations more effective, and allows the enlargement of safety areas or escape routes (Weatherspoon and Skinner, 1996; Catry *et al.,* 2009; Gantaume *et al.,* 2013; O'Connor *et al.* 2017; Xanthopoulos *et al.,* 2006). Regarding this last point, it is dramatically remarkable to recall that the large majority of the victims of the Portugal wildfire events of June 2017 lost their lives nearby the roads, and that 30 people lost their lives in a single road section of about 400m-length (Viegas *et al.,* 2017). Even if it is likely that slower fire growth rates and the increased presence of unburnable areas after the fuel treatments would have improved fire suppression capacity and safety, we did not take into consideration fire suppression in the fire modeling exercise. This was also due to the fact that 1) current fire suppression operations in Mediterranean areas mainly focus on civil protection issues and disregard fire perimeter control (Beighley and Quesinberry, 2004; Oliveira *et al.*, 2016) and 2) coordinating suppression activities based on fuel management infrastructures during large events is challenging (Finney *et al.*, 2003; Keeley, 2002; Oliveira *et al.*, 2016; Rigolot and Viegas, 2002). Yet, as indicated by Oliveira *et al.,* 2016, the high costs of the fuel management strategies impose that fire suppression operations take advantage of the presence of treated areas to reduce area burned beyond a passive effect.

We observed a general pattern in terms of treatment effectiveness related to the single land use size (LAR, MED and LOW strategies): overall, the smallest treatment units (LOW strategy) were less efficient than the largest ones (LAR strategy) in contrasting fire propagation. This points out that, in agro-pastoral areas and for treatments that convert fuels to non-burnable fuels, the creation of large and extended fuel treatment units (unit size 25-50 ha) ensures a greater efficiency in reducing fire exposure with respect to small treatment units (0.5-10 ha). Moreover, from an operational point of view, the LAR strategy is more cost-effective, less time-consuming and easier to be performed in the field, as it concentrates fuel management operations in well-defined large areas. The fact that the LAR strategy was superior to the other two ones could be related to the reduction of the fuelbrand overflight possibilities and the associated ignition of spot fires, as well as to an enhanced potential to block heading fire spread and to enable mostly flanking propagation (Finney, 2007).

As expected, we found that, apart from the fuel treatment strategy, the increase in the percentage of landscape treated (from 2% to 8%) resulted in a reduction of fire exposure indicators. Our results highlighted that in several cases treating 5% of the landscape using the ROAD strategy was more efficient than treating 8% of the study area with other strategies, even at the lowest wind speed conditions. Although we were aware that the increase in the treated areas would have positively influenced the potential to limit fire propagation, we chose to treat relatively small areas (2, 5, and 8% of the landscape), considering that, as indicated by previous works and according to the local land managers indications, performing fuel treatments for vast portions of lands (e.g.: > 10% of a study area) is very challenging or even practically impossible (Calkin *et al.,* 2014; Finney, 2007; Moghaddas *et al.*, 2010). As proved by other studies (Ager *et al.*, 2007; Bradstock *et al.*, 2012; Price, 2012; Salis *et al.*, 2016b; Syphard *et al.*, 2011), treating a small proportion of the landscape (2%) resulted in minimal reduction in wildfire exposure profiles and potential area burned. Yet, preliminary simulations (treated landscape = 0.5% and 1%) showed very limited or null differences among treatment strategies and NO-TREAT conditions in terms of BP, CFL and FS. Despite this, our work showed that even treating low percentages of landscape (e.g.: 5% of the study area) can allow excellent results to limit fire growth when combined with an efficient localization of fuel treatments (e.g.: ROAD strategy).

The results revealed significant variations in the fire exposure profiles in relation to wind intensity, with an apparent growth in the average values of BP, CFL and FS at both landscape and selected WUI values scales as wind speed increased. Simulating fire growth and behavior under severe weather conditions such as intense winds can allow identifying wildfire preferential pathways and hot-spot areas, or estimating potential losses from fires. This is relevant in the light of future climate change and of the increased frequency of extreme weather (EEA, 2017). Furthermore, testing different wind intensity conditions allowed to highlight how diverse fuel treatment strategies and treated area percentages would be able to lower fire growth and behavior. As a general rule, fires burning under mild wind speed conditions and low percentages of area treated are less affected by the spatial treatment pattern because fire growth is smaller and the relative spread rates in the treatment scenarios are not dissimilar to those of the untreated condition (Ager *et al.,* 2010; Finney, 2001). From this point of view, our findings confirmed that the differences in the effectiveness of the fuel treatment scenarios were accentuated by stronger wind conditions (32 km h^{-1}), that is by those conditions associated with the major extreme-behavior fires that could overcome the suppression capabilities of firefighters.

In this work, we hypothesized to perform treatments able to determine the conversion of the treated units into unburnable fuels. The treatments hypothesized (prescribed burning, superficial tillage, and summer irrigation, depending on the land use type) are overall low-cost treatments and could be financially supported by specific EU rural policies and programs (European Commission, 2017) with the aim of preserving and enhancing ecosystems related to agriculture and forestry. In fact, we proved that efficient fuel treatment mosaics can limit wildfire growth and behavior, and can therefore reduce both wildfire losses and suppression costs (e.g.: less aerial interventions). If financially supported, the above treatments can also produce positive economic, social and ecological effects on fire-prone Mediterranean areas by linking virtuous preventive actions to EU payments to local farmers. Furthermore, fuel management approaches can allow reducing the relevant gap between fire prevention and suppression in terms of organizational hierarchy and budget (Bovio et al., 2017; Gebert et al. 2007; Gonzalez-Olabarria and Pukkala, 2011; Thompson et al., 2013). The effects of fuel treatments on fire spread and exposure that we tested in this study are only temporary and last in some months. For instance, the possibility of vegetation resprouting or germination of annual herbs after tilling and/or prescribed burning performed in mid-late June in Sardinia, as well as in other dry climate Mediterranean Basin areas, is typically very low, particularly in terms of potential to create a continuous surface fuel bed able to support surface fires. This is mostly due to the fact that rain events, from June until September (which is the typical fire season period), are quite rare and limited in terms of total amount, and the maximum temperatures are often above 30° during summer, which limit soil water content and plant resprouting or growth in that period of the year, after the treatments. The limited longevity of individual treatments would therefore impose a scheduled program of summer irrigation or late-spring prescribed burning. Regarding the latter point, land managers could also promote the selection of land use units according to 2-3 years spatial rotation criteria, and dynamic single treatments units could be added to priority fuel management target areas.

The use of grazing animals as cost-effective, non-toxic, and non-polluting solution for reducing 1-hr and 10-hr fuel loads and continuity and limiting fire behavior was proposed by previous works for different ecosystems (Diamond *et al.,* 2009; Franca *et al.,* 2012; Green and Newell, 1982; Hart, 2001; Lovreglio *et al.,* 2014; Ruiz-Mirazo and Robles, 2012). However, several Sardinian wildfires were found to spread fast also in grazed areas, and in recent years the largest events of the island were not blocked but only slowed down by grazed landscapes (Nudda *et al.,* 2015, 2016, 2017; Salis *et al.,* 2012). In addition, in Mediterranean areas, common concerns with herbivores are mostly related to overgrazing, soil erosion and even degradation of shrublands and forests, particularly for goats (Caballero *et al.,* 2009; Kairis *et al.,* 2015; Vacca *et al.,* 2003). For the above reasons, we did not use grazing as preferential fuel treatment option.

The application of fire spread models, previously calibrated and validated for Mediterranean fire-prone ecosystems and landscapes, may foster designing optimized fuel management strategies and spatial arrangements, as well as prioritizing the most exposed areas. The methodology proposed in this paper can be replicated in other Mediterranean areas and elsewhere and allows to simulate diverse fuel management scenarios while analyzing their performances and effectiveness by objective measures like burn probability, fire intensity and fire size. The proposed approach could have large application in Sardinia, as the most recent regional programs for rural and inner areas development, as well as forest and fire management directives and planning, highlight the relevance of fire prevention and land management to reduce wildfire risk, preserve valued landscapes and ecosystems, promote the multifunctional use of agricultural areas, and protect anthropic values under current conditions and those expected in the future under climate change in Mediterranean areas (Sardinia Regional

Government, 2014, 2016, 2017). Likewise, ongoing regional fuel treatment programs aiming at reducing fire risk are mainly based on expert-based evaluations and decisions and are limited by a number of constraints, and could benefit from large-scale, comprehensive and optimized spatial design of fuel treatments according to preliminary quantitative assessments of fuel treatment effects on wildfire spread and behavior. Yet, assessing quantitatively wildfire exposure over large landscapes remains challenging, since several factors that affect fire ignitions, spread and suppression potential are difficult to be captured (Ager *et al.,* 2014; Calkin *et al.,* 2015; Fernandes, 2013). In addition, even if the MTT fire models family (FSim, FSPro, Flammap, Randig) was proved to have potential in quantitatively replicating large wildfires, in terms of predicting potential area burned, size and shape of perimeters, or potential burn probability and fire intensity (e.g.: Ager *et al.*, 2014; Alcasena *et al.* 2016; Finney *et al.*, 2011; Salis *et al.*, 2013), these models have a number of limitations. For instance, we recall that: (i) fire–atmosphere interactions are not modeled, so that crown fire activity, spotting phenomena and spread rates can be underestimated with respect to actual events (Cruz and Alexander, 2010); (ii) the spatial input data used for surface and crown fuels were assigned according to Corine land-cover classes and forest inventory data, which can add additional uncertainty; (iii) the 25-m spatial resolution may not fully capture fine scale fuel bed characteristics and conditions of both treated and untreated areas; (iv) a 1% constant spot probability for the three wind speed scenarios might represent a simplified condition.

5. Conclusions

This work presents a wildfire exposure assessment framework, based on the MTT fire spread algorithm, that allows characterizing the performances of diverse fuel treatment mosaics related to diverse spatial arrangement strategies on limiting wildfire spread in an agro-pastoral Mediterranean area. The proposed approach permits to highlight the variations in wildfire exposure profiles due to different treatment scenarios and discriminate the strategies according to their effectiveness using an objective quantitative assessment approach. We demonstrate that fuel treatment strips nearby the road network represent the most efficient spatial strategy for herbaceous fuel type dominated landscapes.

The methodology and the findings of this work can provide guidelines and suggestions for land managers and policy makers of the study area and of neighboring Mediterranean areas, particularly for rangelands and wooded pastures (e.g., *dehesas* or *montados*). A number of considerations, preferences and constraints used in this study for the spatial localization, priorities and objectives of fuel treatments has the potential to be finely tuned for strategic planning of landscape scale fuel treatments and fire management programs. This work increases knowledge and awareness of spatial arrangements of fuel treatments in herbaceous areas with limited portions of land to be treated, and may support the identification and planning of the most effective strategies and spatial locations of fuel treatments.

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Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area

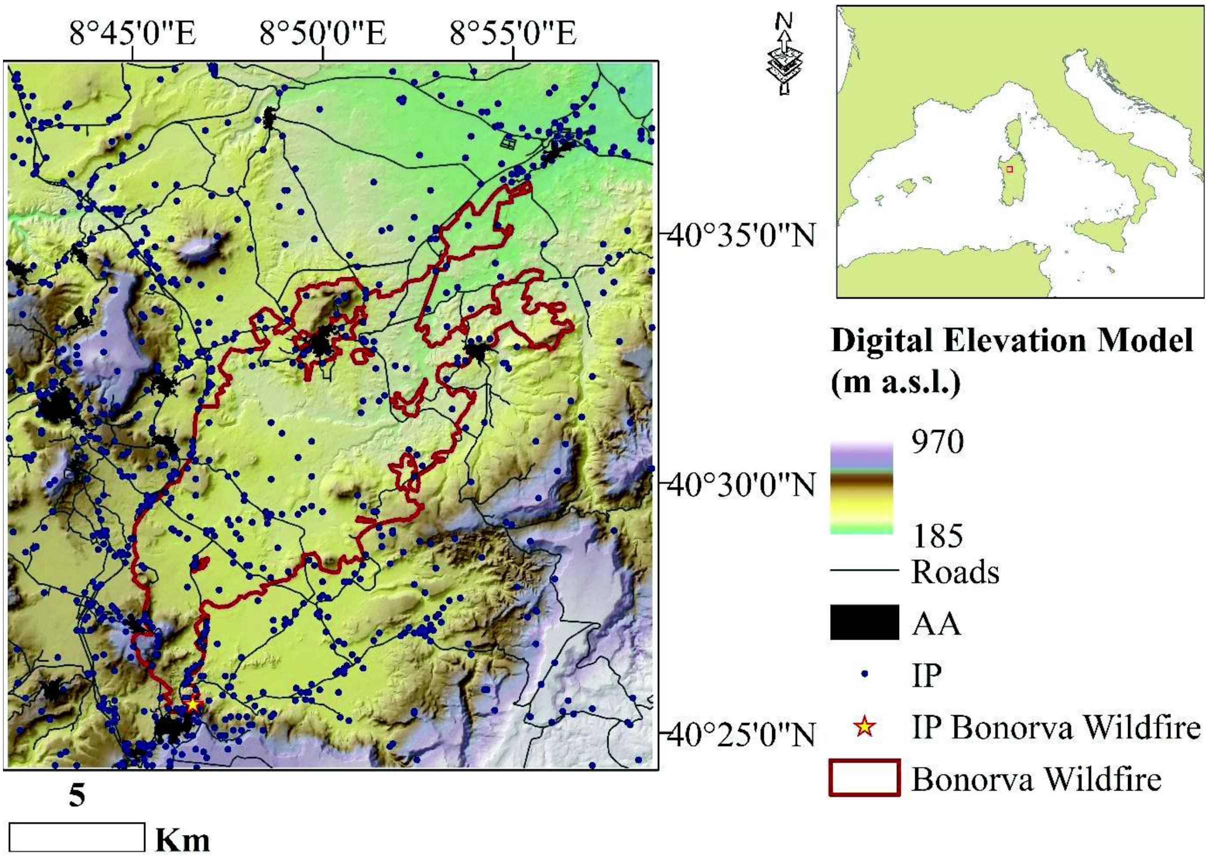

Fig. 1. Digital elevation model (DEM) of the study area (North Sardinia, Italy) along with roads and urban and anthropic areas (AA). The study area was affected by a very large wildfire (Bonorva, 23 July 2009, about 10,600 ha of size (red polygon)), which was one of the largest events ever observed in Sardinia since ‘90s. The fire ignition points (IP) of the study period 1998-2015 are showed in blue.

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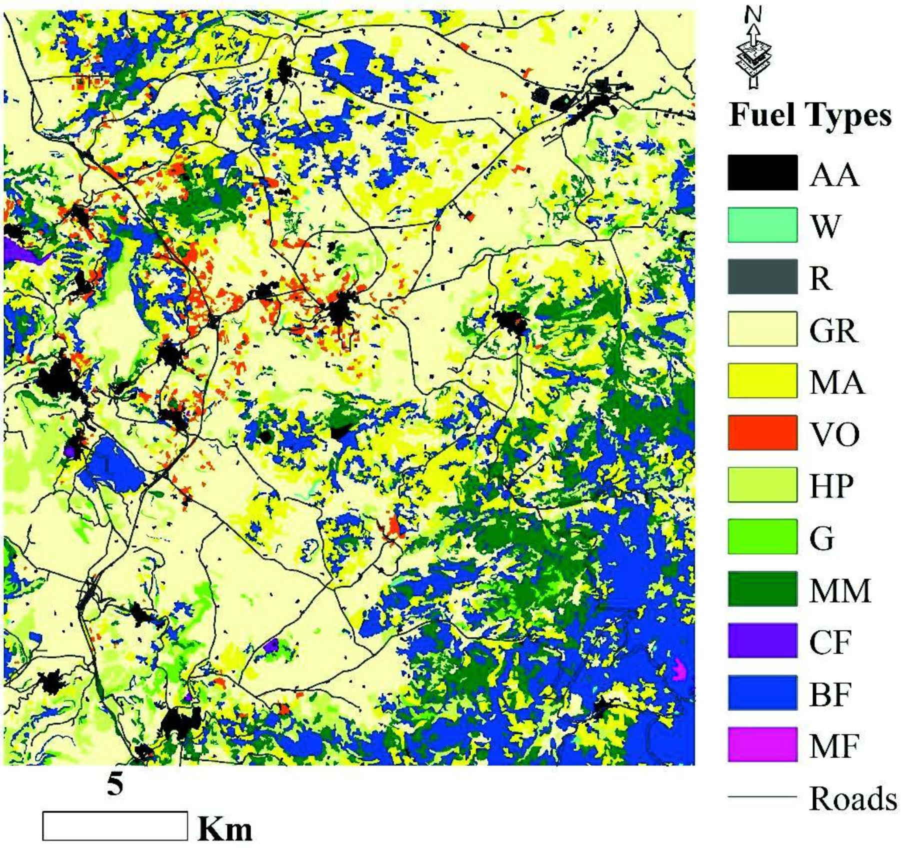


Fig. 2. Main fuel types of the study area. AA = urban and anthropic areas; W = water bodies; R = rocks; S = sands; GR = grasslands; MA = mixed agricultural areas; VO = vineyards and orchards; HP = herbaceous pastures; G = garrigue; MM = Mediterranean maquis; CF = conifer forests; BF = broadleaf forests;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

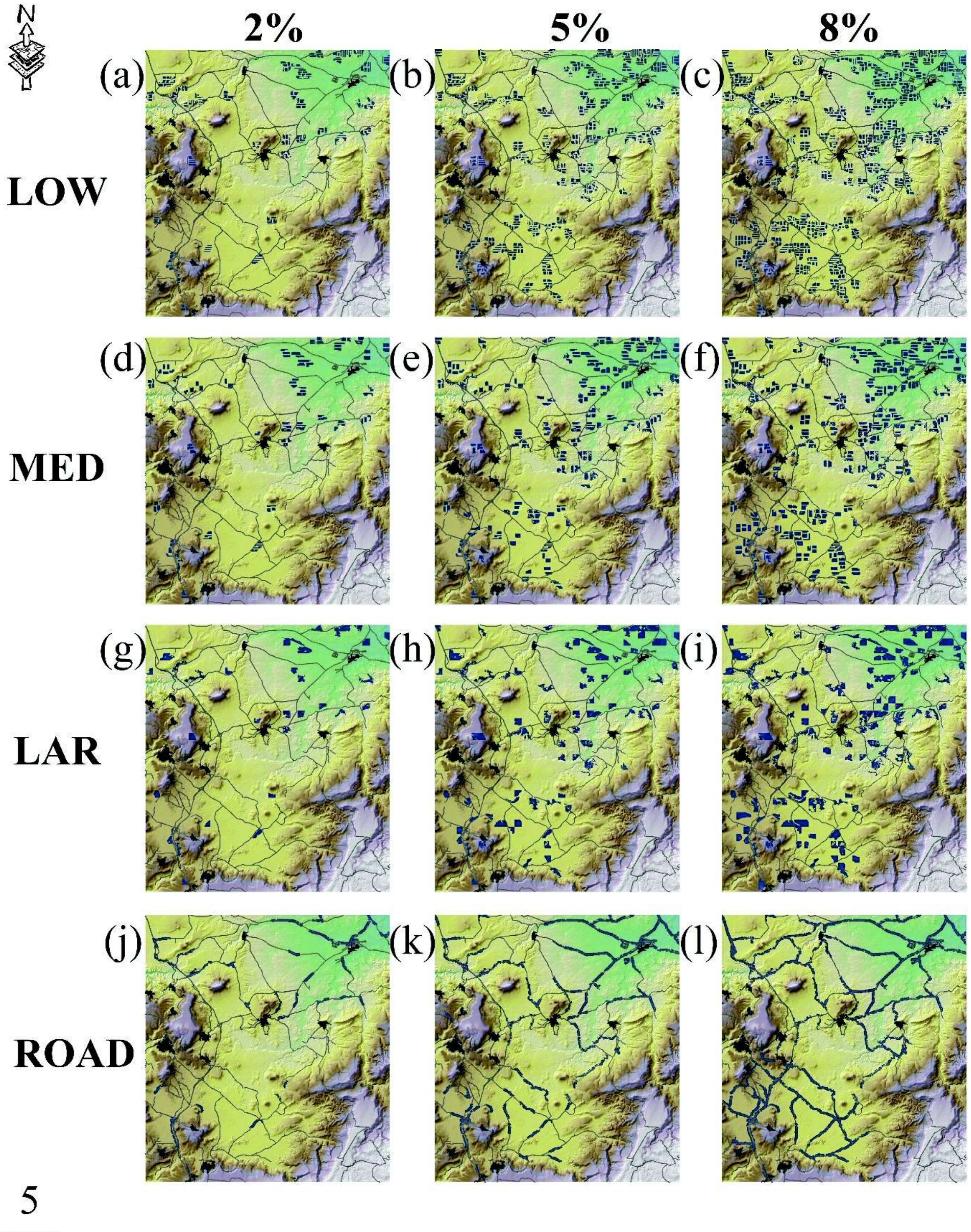

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
Fuel Treatment Units
AA
Roads

Fig. 3. Maps of the fuel treatment alternatives tested (low size treatment units (LOW, a, b, c), medium size treatment units (MED, d, e, f), large size treatment units (LAR, g, h, i), treatment units nearby roads (ROAD, j, k, l), considering 2%, 5% and 8% of the landscape area treated.

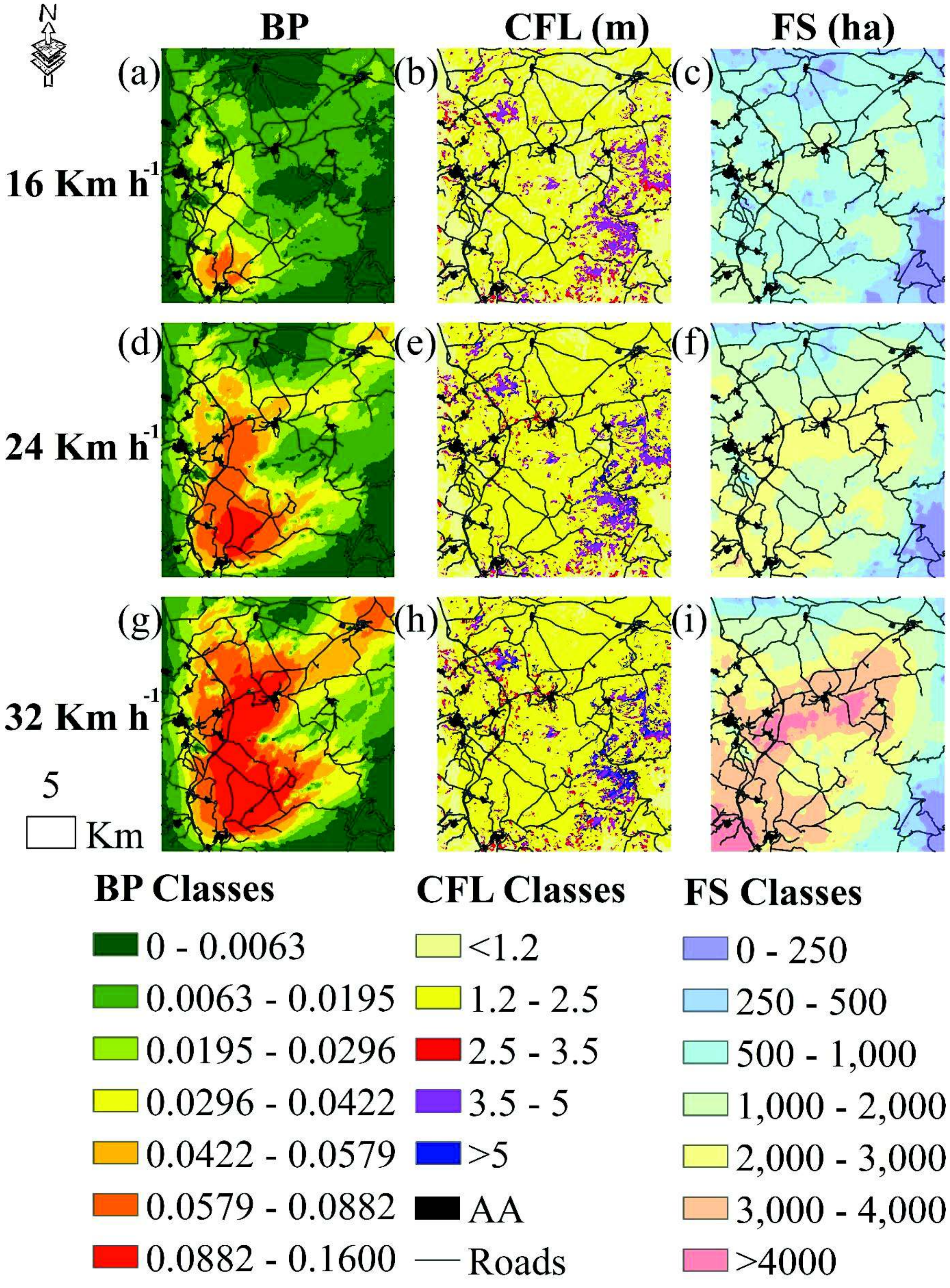

BP
CFL (m)
FS (ha)
N
(a)
(b)
(c)
16 Km h^{-1}
(d)
(e)
(f)
24 Km h^{-1}
(g)
(h)
(i)
32 Km h^{-1}
5
Km
BP Classes
0 - 0.0063
0.0063 - 0.0195
0.0195 - 0.0296
0.0296 - 0.0422
0.0422 - 0.0579
0.0579 - 0.0882
0.0882 - 0.1600
CFL Classes
<1.2
1.2 - 2.5
2.5 - 3.5
3.5 - 5
>5
AA
Roads
FS Classes
0 - 250
250 - 500
500 - 1,000
1,000 - 2,000
2,000 - 3,000
3,000 - 4,000
>4000

Fig. 4. Maps of burn probability (BP (a, d, g)), conditional flame length (CFL (b, e, h)) and fire size (FS (c, f, i)) for the NO-TREAT condition, considering different wind speed conditions (16, 24 and 32 km h^{-1}).

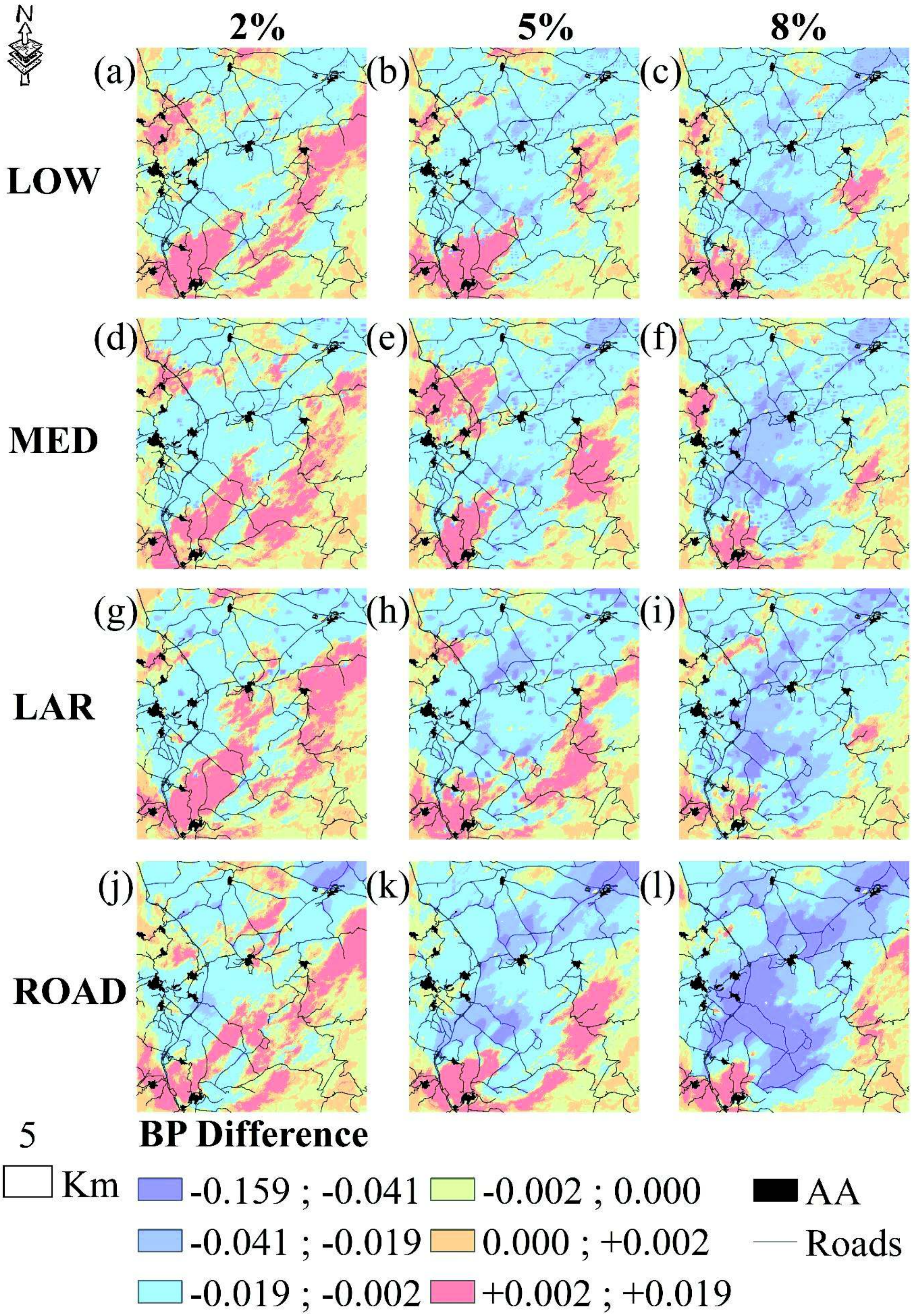

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
BP Difference
-0.159 ; -0.041
-0.041 ; -0.019
-0.019 ; -0.002
-0.002 ; 0.000
0.000 ; +0.002
+0.002 ; +0.019
AA
Roads

Fig. 5. Maps of the differences in burn probability (BP) between the four fuel treatment alternatives (LOW, MED, LAR, ROAD) and the NO-TREAT condition, considering the three percentages of landscape treated (2%, 5%, and 8%), and a wind speed of 32 km h^{-1}

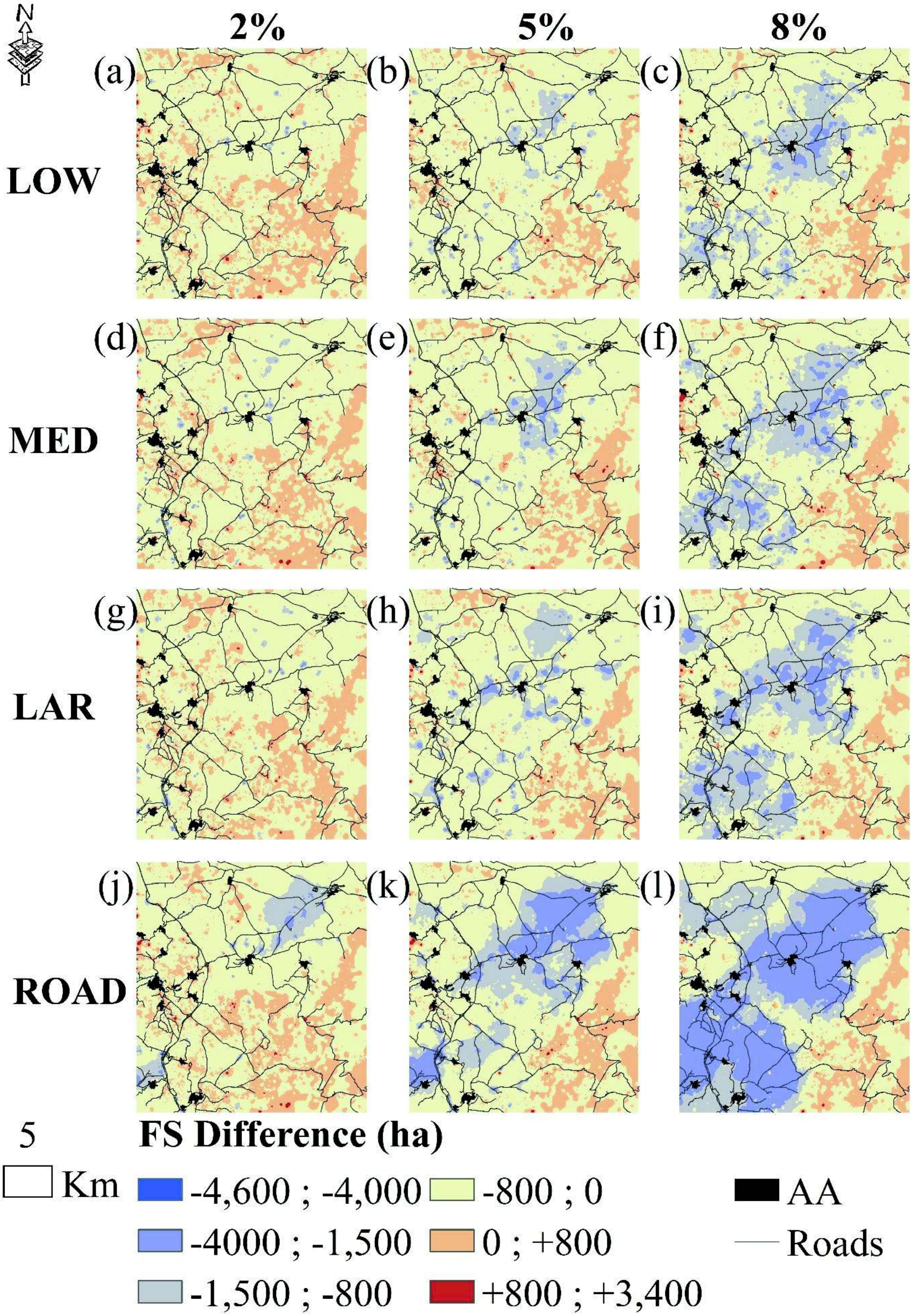

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
FS Difference (ha)
-4,600 ; -4,000
-4000 ; -1,500
-1,500 ; -800
-800 ; 0
0 ; +800
+800 ; +3,400
AA
Roads

Fig. 6. Maps of the differences in fire size (FS) between the four fuel treatment alternatives (LOW, MED, LAR, ROAD) and the NO-TREAT condition, considering the three percentages of landscape treated (2%, 5%, and 8%), and a wind speed of 32 km h^{-1}

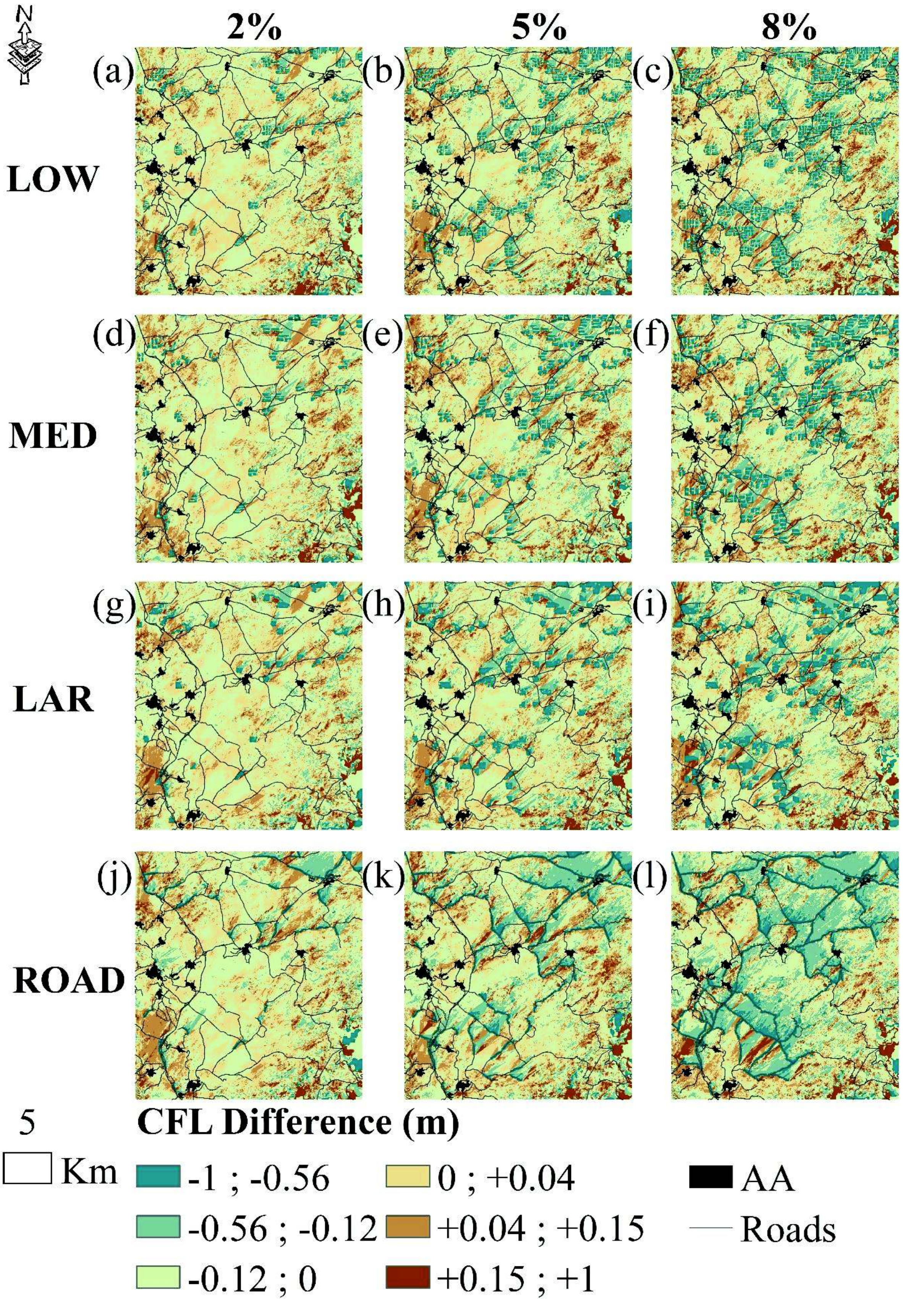

N
2%
5%
8%
LOW
MED
LAR
ROAD
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
5
Km
CFL Difference (m)
-1 ; -0.56
-0.56 ; -0.12
-0.12 ; 0
0 ; +0.04
+0.04 ; +0.15
+0.15 ; +1
AA
Roads

Fig. 7. Maps of the differences in conditional flame length (CFL) between the four fuel treatment alternatives (LOW, MED, LAR, ROAD) and the NO-TREAT condition, considering the three percentages of landscape treated (2%, 5%, and 8%), and a wind speed of 32 km h^{-1}

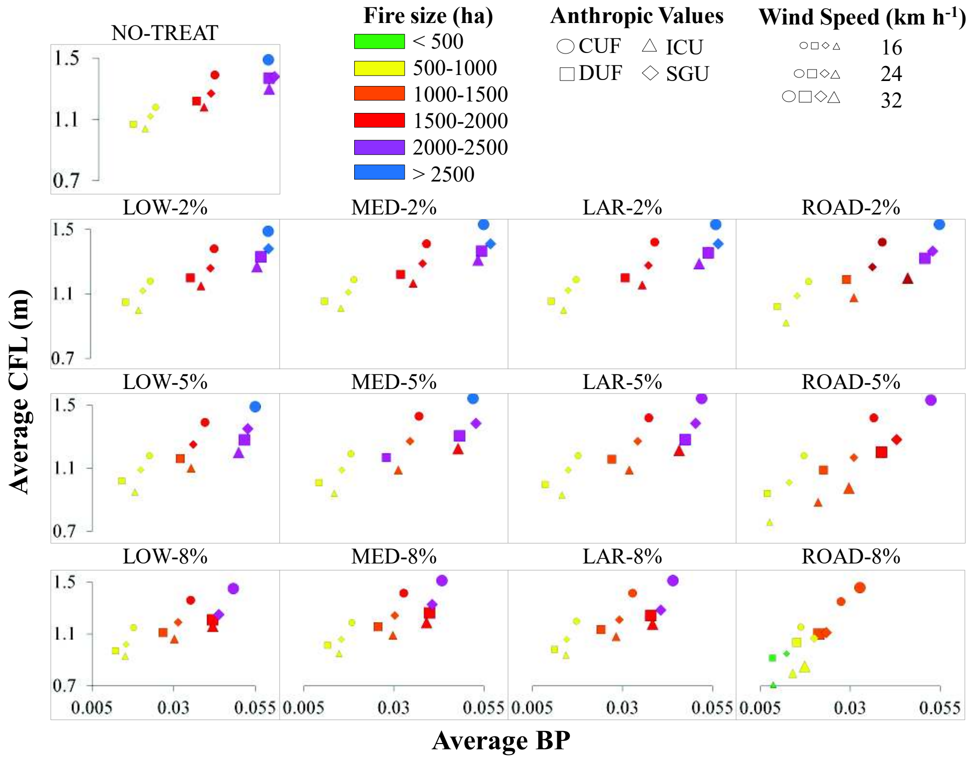


Fig. 8. Scatterplots of average burn probability (BP) vs average conditional flame length (CFL) in the vicinity (150 m buffer) of selected anthropic values (continuous urban fabric (CUF), discontinuous urban fabric (DUF), industrial and commercial units (ICU), and sport and green urban areas (SGU)). We show the results obtained for the whole set of fuel treatment alternatives and wind speed conditions analyzed in this study. Each symbol is colored and scaled according to the average simulated fire size and wind speed scenario, respectively.

Figure 1

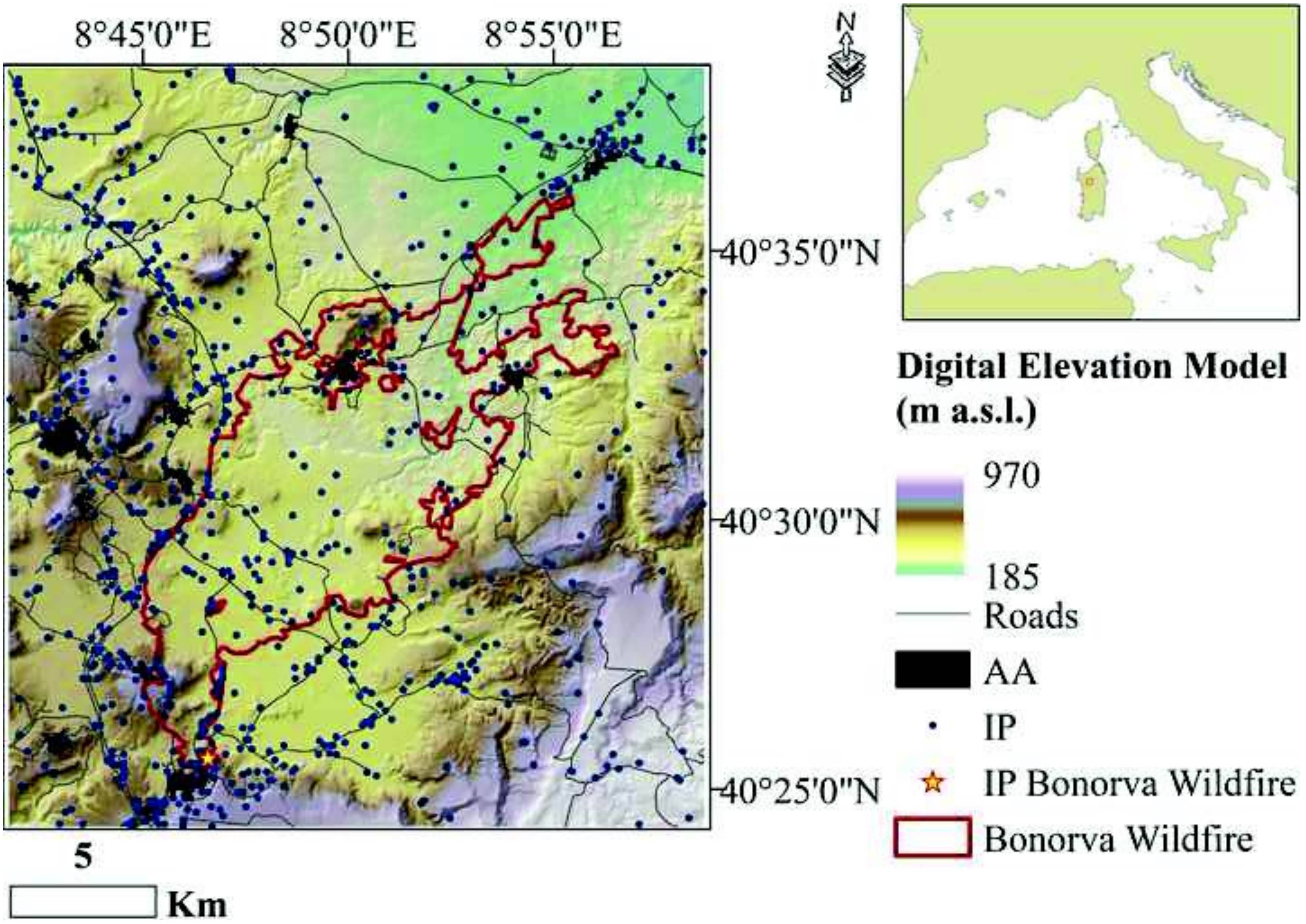

8°45'0"E
8°50'0"E
8°55'0"E
40°35'0"N
40°30'0"N
40°25'0"N
N
Digital Elevation Model
(m a.s.l.)
970
185
Roads
AA
IP
IP Bonorva Wildfire
Bonorva Wildfire
5
Km

Figure 2

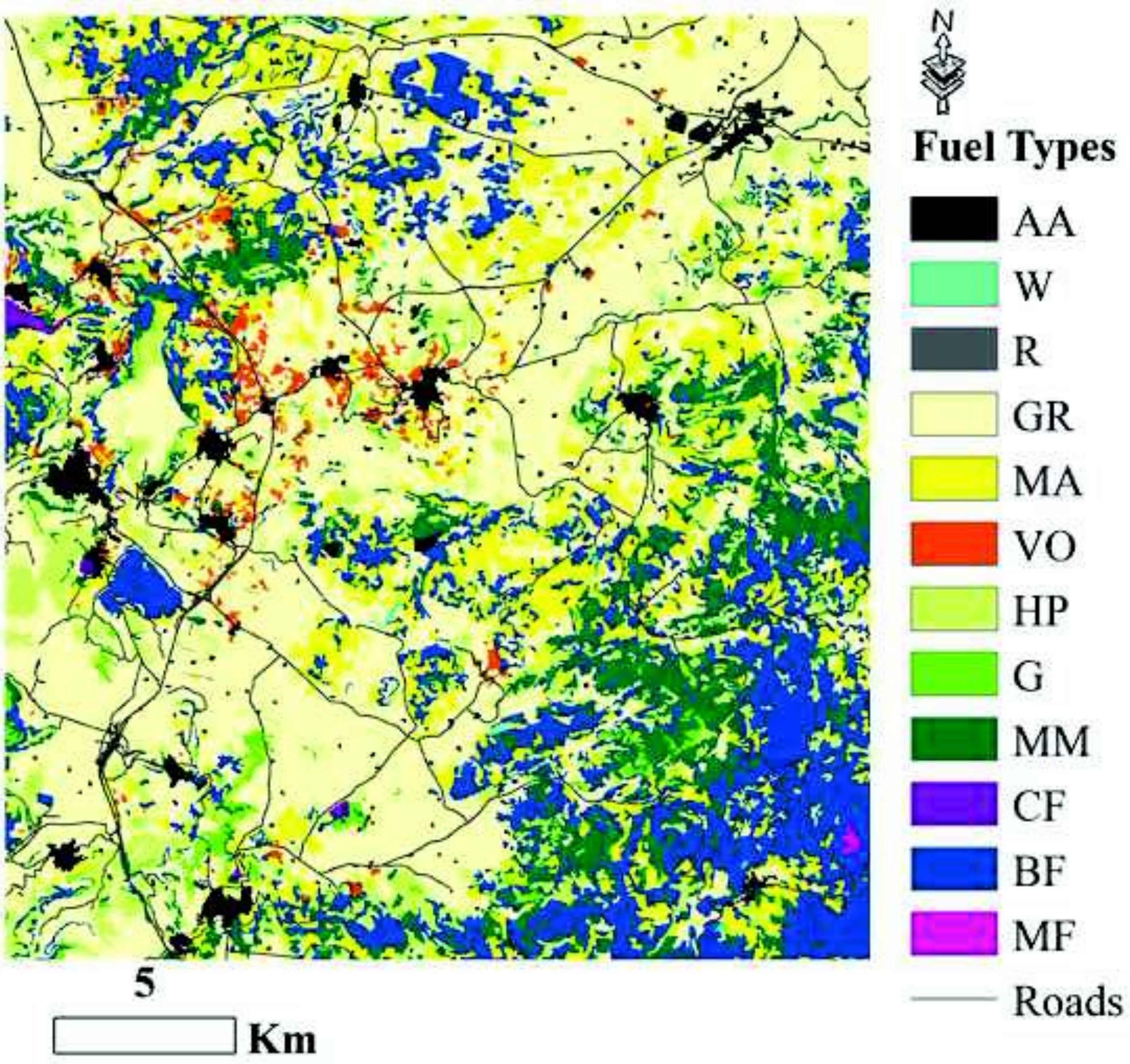


Figure 3

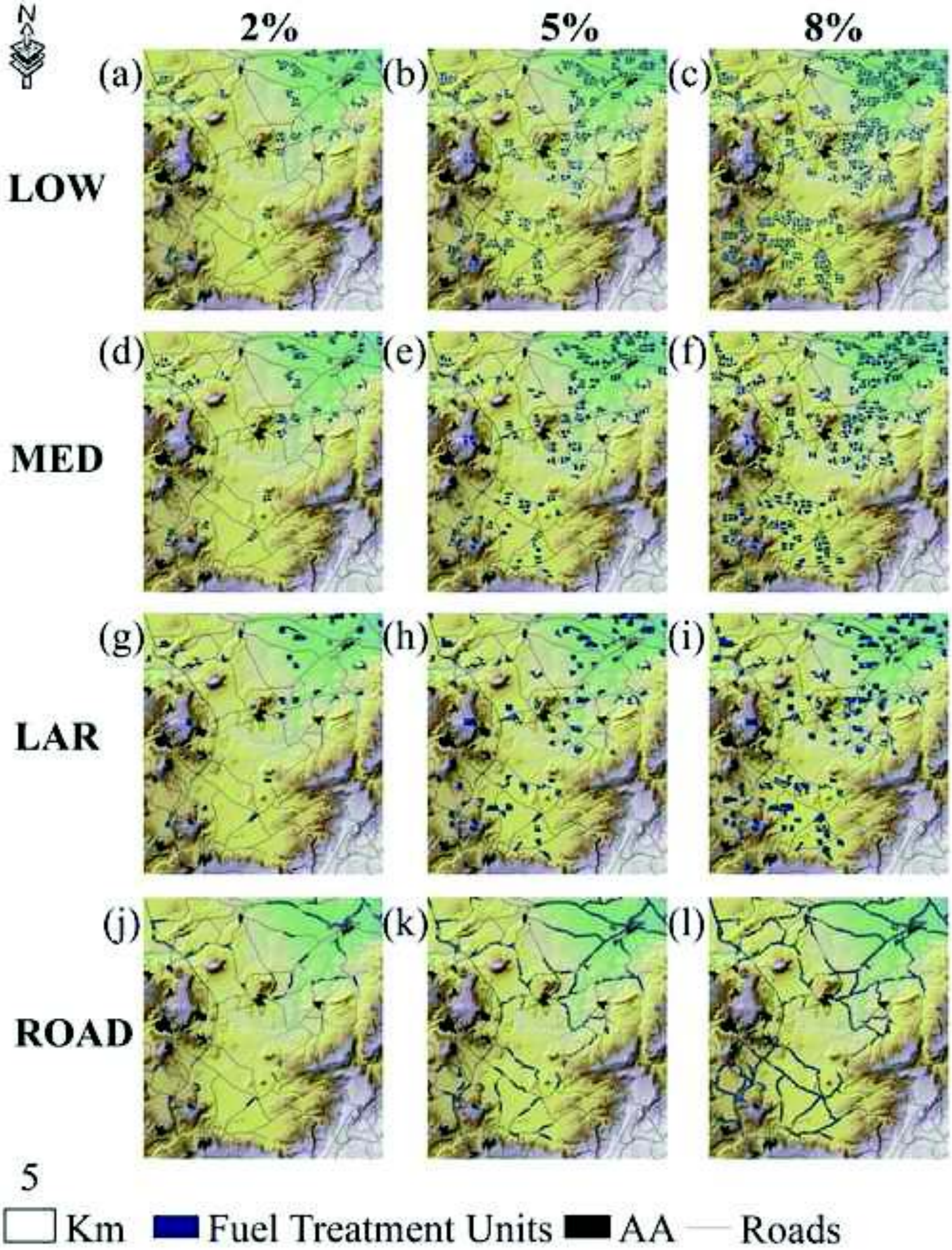

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
Fuel Treatment Units
AA
Roads

Figure 4

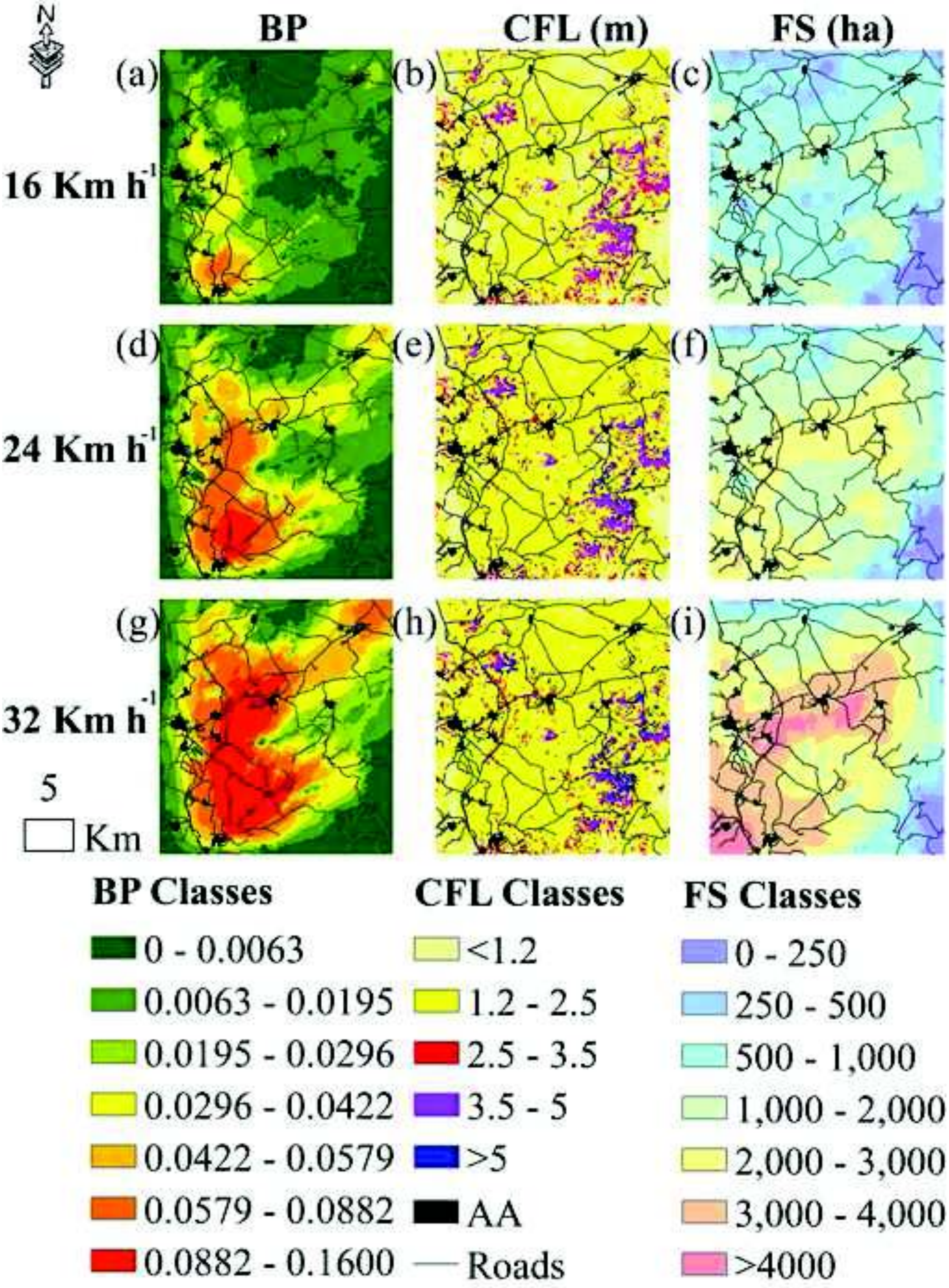

N
BP
CFL (m)
FS (ha)
(a)
(b)
(c)
16 Km h-1
(d)
(e)
(f)
24 Km h-1
(g)
(h)
(i)
32 Km h-1
5
Km
BP Classes
0 - 0.0063
0.0063 - 0.0195
0.0195 - 0.0296
0.0296 - 0.0422
0.0422 - 0.0579
0.0579 - 0.0882
0.0882 - 0.1600
CFL Classes
<1.2
1.2 - 2.5
2.5 - 3.5
3.5 - 5
>5
AA
Roads
FS Classes
0 - 250
250 - 500
500 - 1,000
1,000 - 2,000
2,000 - 3,000
3,000 - 4,000
>4000

Figure 5

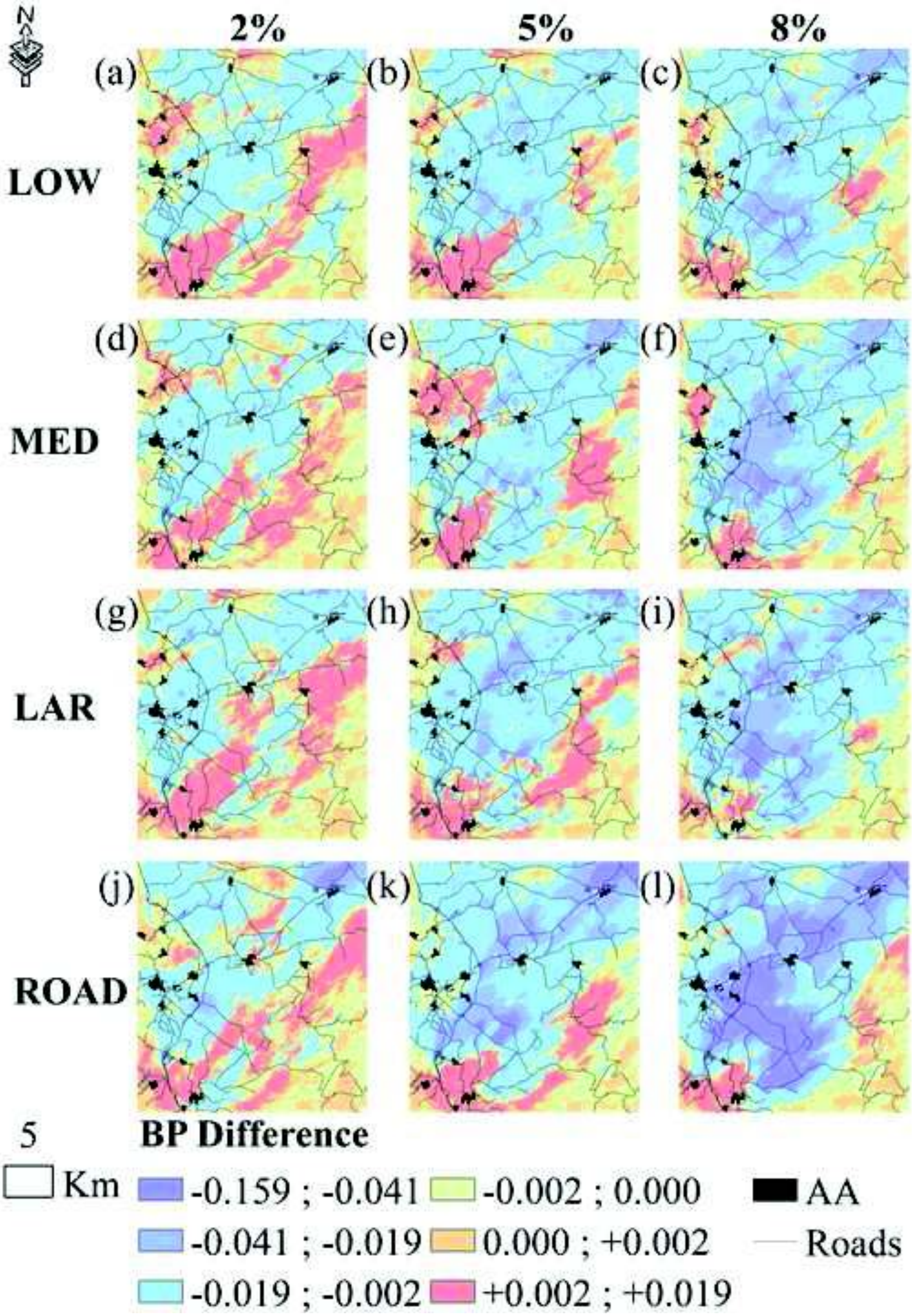

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
BP Difference
-0.159 ; -0.041
-0.041 ; -0.019
-0.019 ; -0.002
-0.002 ; 0.000
0.000 ; +0.002
+0.002 ; +0.019
AA
Roads

Figure 6

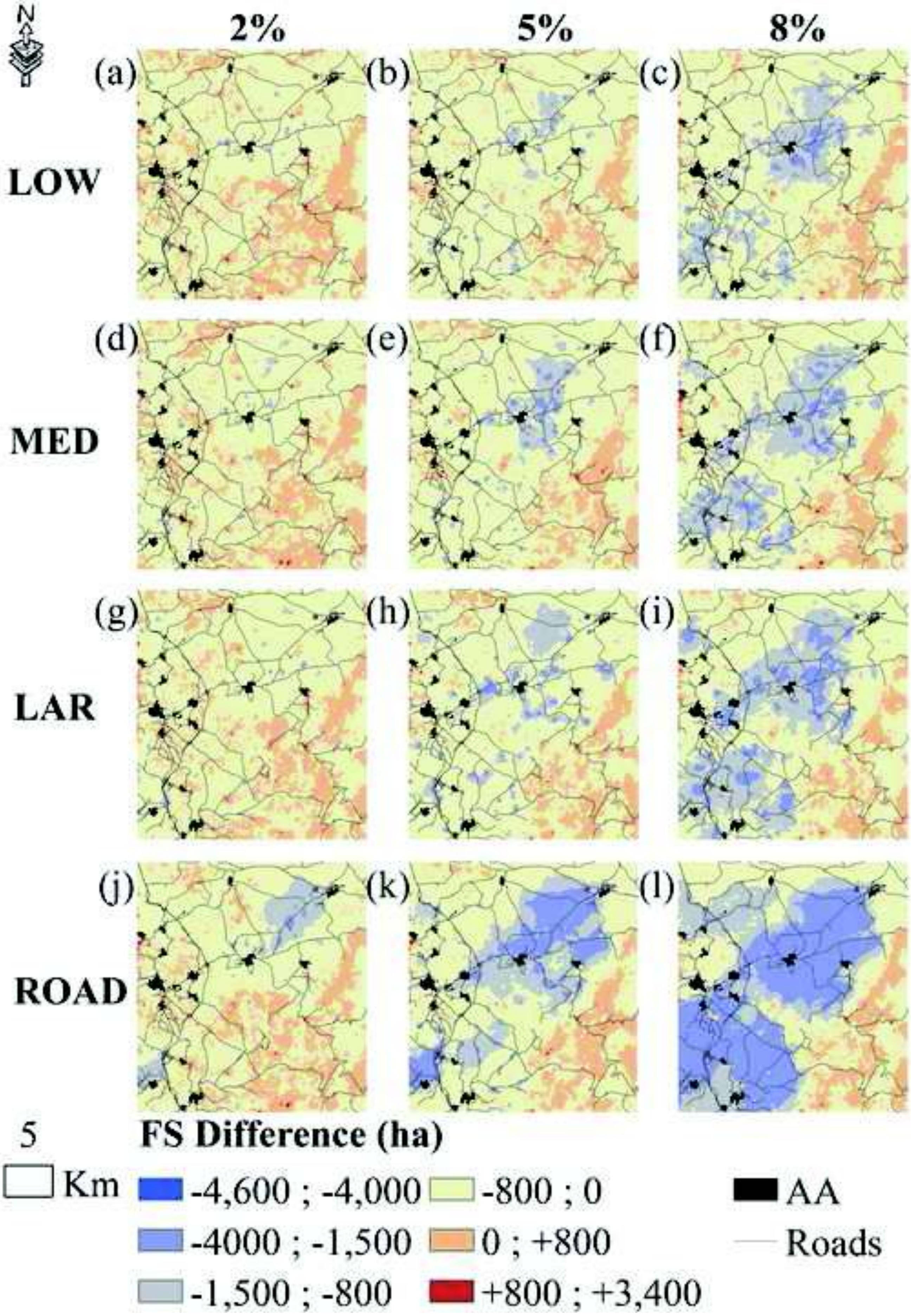

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
FS Difference (ha)
-4,600 ; -4,000
-4000 ; -1,500
-1,500 ; -800
-800 ; 0
0 ; +800
+800 ; +3,400
AA
Roads

Figure 7

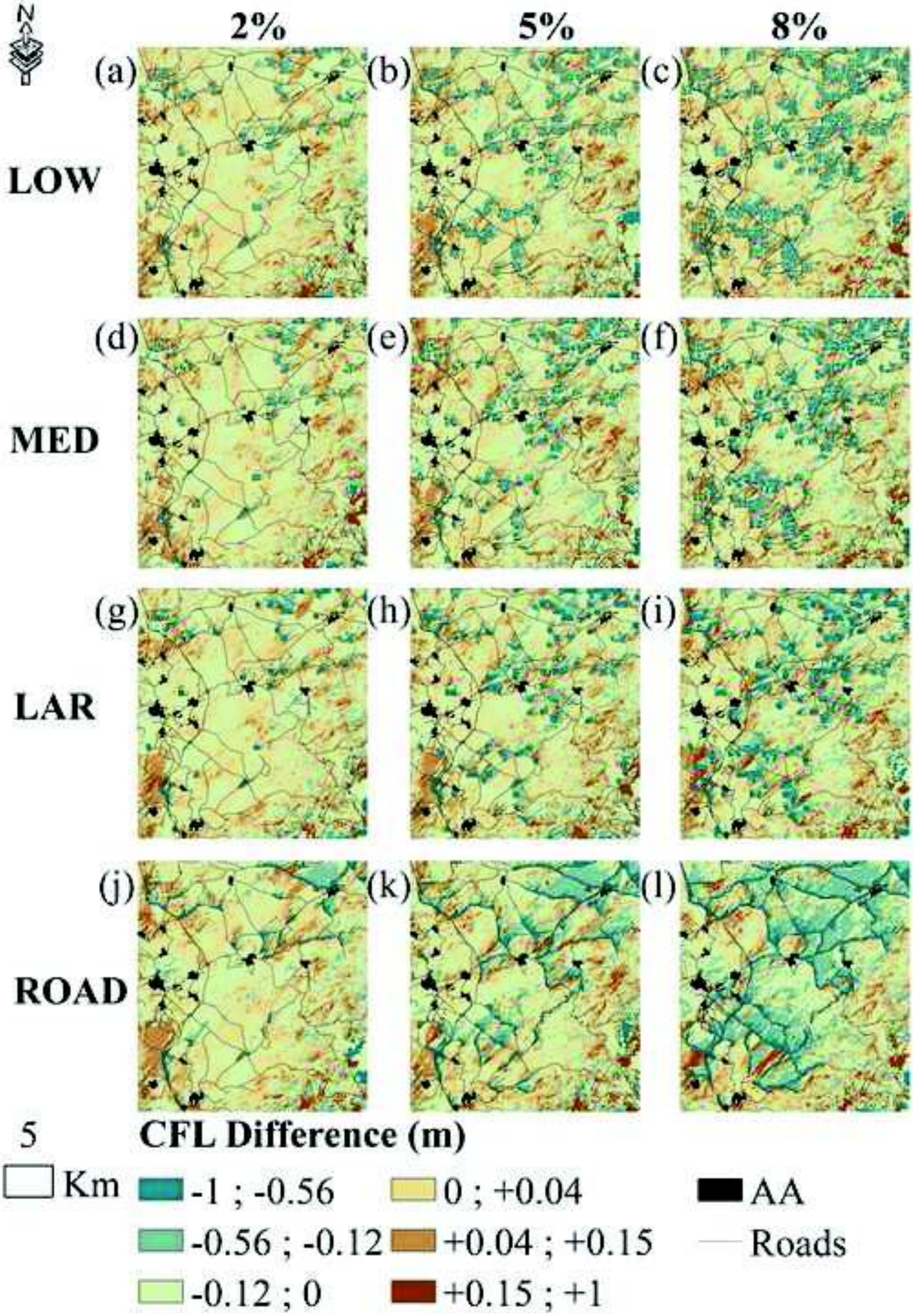
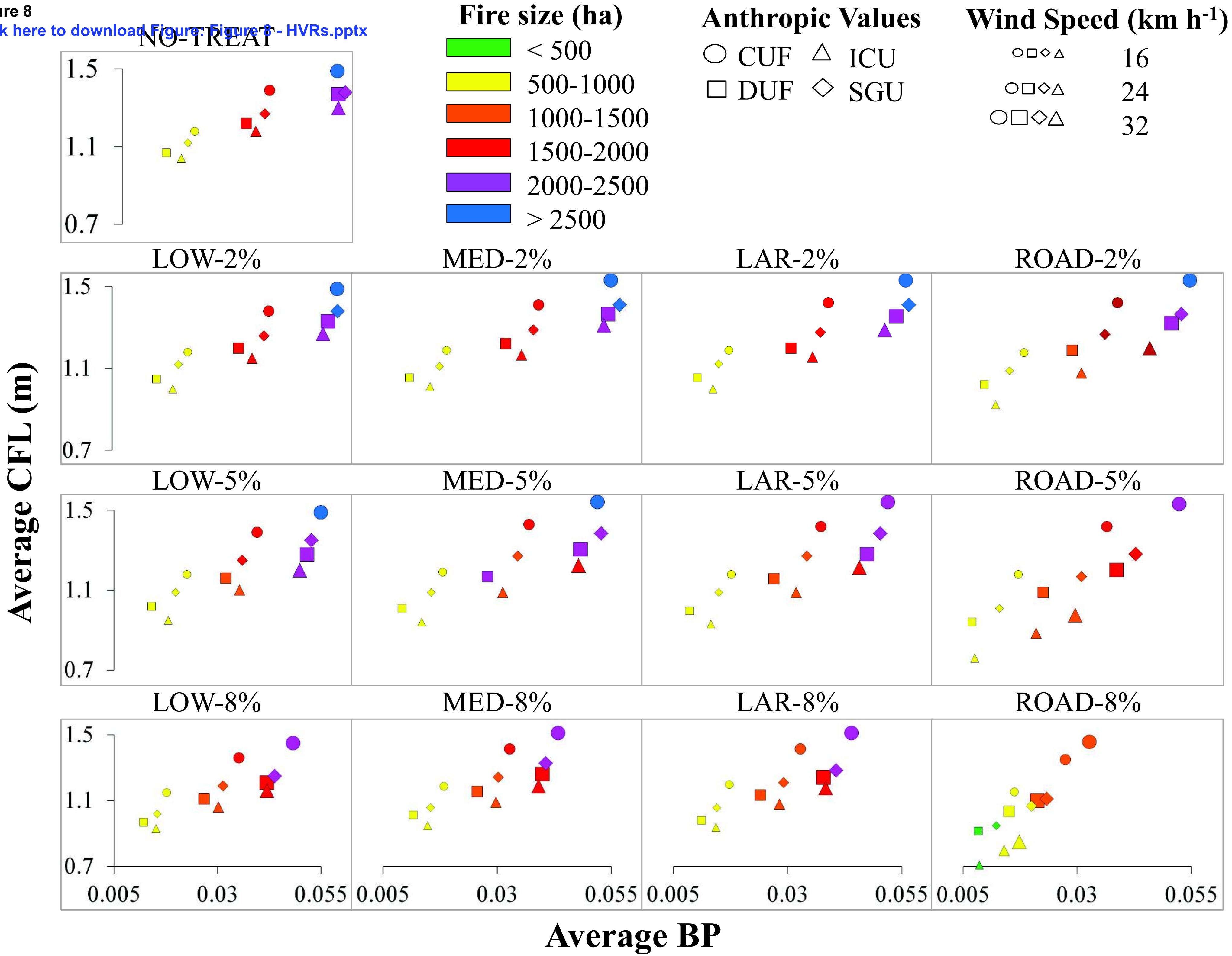

N
2%
5%
8%
(a)
(b)
(c)
LOW
(d)
(e)
(f)
MED
(g)
(h)
(i)
LAR
(j)
(k)
(l)
ROAD
5
Km
CFL Difference (m)
-1 ; -0.56
-0.56 ; -0.12
-0.12 ; 0
0 ; +0.04
+0.04 ; +0.15
+0.15 ; +1
AA
Roads

Figure 8


NO-TREAT
Fire size (ha)
🟩 < 500
🟨 500-1000
🟧 1000-1500
🟥 1500-2000
🟪 2000-2500
🟦 > 2500
Anthropic Values
○ CUF
△ ICU
□ DUF
◇ SGU
Wind Speed (km h-1)
○□◇△ 16
○□◇△ 24
○□◇△ 32
LOW-2%
MED-2%
LAR-2%
ROAD-2%
LOW-5%
MED-5%
LAR-5%
ROAD-5%
LOW-8%
MED-8%
LAR-8%
ROAD-8%
1.5
1.1
0.7
0.005
0.03
0.055
Average CFL (m)
Average BP

Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area

Table 1. Criteria used to select the fuel treatment units polygons. Overall, we tested 13 fuel treatment conditions (NO-TREAT + 4 fuel treatment alternatives x 3 percentages of area treated)

CRITERIA	DESCRIPTION
Treatment constraints	We allowed treatments in areas covered by specific herbaceous fuels (annual crops with permanent crops (241), non-irrigated arable land (211), and permanently irrigated land (212) (as derived from Sardinia Land Use Map 2008)). Treatments were constrained to areas with low terrain slope (< 10°)
Percentage of landscape treated	We treated 2% (≈1,200 ha), 5% (≈3,000 ha) and 8% (≈4,800 ha) of the study area
Single treatment units	We performed treatments in single units with given size classes [low size (LOW, 0.5-10 ha), medium size (MED, 10-25 ha), and large size (LAR, 25-50 ha)] + in a 100 m buffer around the road network (ROAD).
Spatial strategy	For all treatment alternatives, the single units were located nearby random priority areas which determined the reference center of each treatment block. We first randomly attributed a treatment prioritization order to each LAR polygon. We then selected a set of LAR fuel treatment units so that a landscape area treated of 2%, 5% and 8% was obtained. The fuel treatment units of the MED and LOW strategies were selected in the closest neighboring of the selected LAR polygons, and was constrained to a 25x25 m Fishnet cells included in the LAR polygons or located within a distance of 100 m to the LAR polygons, only in treatable areas (slope < 10°, Corine classes 211, 212, 241). We also imposed that the distance among single units was greater than or equal to 100 m, so that the treated patches were close but not jammed together. The selection of the ROAD polygons was constrained by the intersection of the road network buffer and the 25x25 m Fishnet cells included in the LAR polygons or located within a distance of 2500 m to the selected LAR polygons, only in treatable areas (slope < 10°, Corine classes 211, 212, 241)
Fuel treatment type	We converted treated units to non-burnable areas (by superficial tillage & prescribed burning (241 & 211) or summer irrigation (212))

Table 2. Average and standard deviation values of BP at landscape scale for each fuel treatment alternative, percentage of landscape treated and wind speed condition. Minimum and maximum values of BP are reported under parenthesis.

Wind speed (km h^{-1})	Landscape treated (%)	Fuel Treatment Alternative				
		NO-TREAT	LOW	MED	LAR	ROAD
16		1.36E-02 ± 1.22E-02				
	2%		1.31E-02 ± 1.15E-02	1.31E-02 ± 1.18E-02	1.31E-02 ± 1.21E-02	1.28E-02 ± 1.17E-02
	5%		1.24E-02 ± 1.13E-02	1.24E-02 ± 1.17E-02	1.19E-02 ± 1.13E-02	1.14E-02 ± 1.12E-02
	8%		1.17E-02 ± 1.08E-02	1.11E-02 ± 1.05E-02	1.09E-02 ± 1.04E-02	9.33E-03 ± 1.03E-02
24		2.84E-02 ± 2.33E-02				
	2%		2.77E-02± 2.38E-02	2.74E-02 ± 2.27E-02	2.71E-02 ± 2.24E-02	2.65E-02 ± 2.30E-02
	5%		2.54E-02 ± 2.15E-02	2.56E-02 ± 2.29E-02	2.47E-02 ± 2.18E-02	2.31E-02 ± 2.19E-02
	8%		2.41E-02 ± 2.12E-02	2.31E-02 ± 2.04E-02	2.20E-02 ± 2.08E-02	1.66E-02 ± 1.78E-02
32		4.42E-02 ± 3.61E-02				
	2%		4.21E-02 ± 3.51E-02	4.20E-02 ± 3.50E-02	4.20E-02 ± 3.60E-02	4.07E-02 ± 3.47E-02
	5%		3.89E-02 ± 3.39E-02	3.87E-02 ± 3.45E-02	3.74E-02 ± 3.33E-02	3.38E-02 ± 3.22E-02
	8%		3.62E-02 ± 3.15E-02	3.42E-02 ± 3.00E-02	3.27E-02 ± 3.06E-02	2.22E-02 ± 2.45E-02

Table 3. *p*-values of the pairwise comparison between NO-TREAT and the fuel treatment alternatives for BP, FS and CFL values and the wind speed conditions tested in this study. Significant differences between NO-TREAT and treatment alternatives were indicated by asterisk (*p*-value <0.05). Pairwise comparison was carried out by the non-parametric Wilcoxon signed rank test.

TREATMENT PAIRWISE COMPARISON	BP			FS			CFL		
	Wind Speed (km h^{-1})								
	16	24	32	16	24	32	16	24	32
NO-TREAT vs LOW-2%	0.051	0.080	0.000*	0.000*	0.000*	0.000*	0.160	0.110	0.030*
NO-TREAT vs MED-2%	0.070	0.008*	0.000*	0.000*	0.000*	0.000*	0.320	0.051	0.021*
NO-TREAT vs LAR-2%	0.030*	0.000*	0.000*	0.000*	0.000*	0.000*	0.060	0.053	0.004*
NO-TREAT vs ROAD-2%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.070	0.090	0.010*
NO-TREAT vs LOW-5%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs MED-5%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs LAR-5%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs ROAD-5%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs LOW-8%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs MED-8%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs LAR-8%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
NO-TREAT vs ROAD-8%	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*

Table 4. Average and standard deviation values of FS at landscape scale for each fuel treatment alternative, percentage of landscape treated and wind speed condition. Minimum and maximum values of FS are reported under parenthesis.

Wind speed (km h^{-1})	Landscape treated (%)	Fuel Treatment Alternative				
		NO-TREAT	LOW	MED	LAR	ROAD
16		769 ± 302				
	2%		743 ± 300	740 ± 301	732 ± 304	723 ± 303
	5%		704 ± 300	696 ± 300	677 ± 297	641 ± 301
	8%		662 ± 287	640 ± 295	628 ± 292	543 ± 303
24		1,555 ± 681				
	2%		1,503 ± 664	1,494 ± 662	1,482 ± 673	1,440 ± 671
	5%		1,396 ± 626	1,385 ± 631	1,348 ± 635	1,234 ± 628
	8%		1,317 ± 596	1,281 ± 592	1,213 ± 579	939 ± 571
32		2,326 ± 1,178				
	2%		2,211 ± 1,142	2,193 ± 1,144	2,186 ± 1,155	2,105 ± 1,133
	5%		2,040 ± 1,066	2,011 ± 1,063	1,950 ± 1,059	1,719 ± 984
	8%		1,879 ± 962	1,820 ± 940	1,727 ± 915	1,193 ± 788

Table 5. Average and standard deviation values of CFL at landscape scale for each fuel treatment alternative, percentage of landscape treated and wind speed condition. Minimum and maximum values of CFL are reported under parenthesis.

Wind speed (km h^{-1})	Landscape treated (%)	Fuel Treatment Alternative				
		NO-TREAT	LOW	MED	LAR	ROAD
16		1.28 ± 0.88				
	2%		1.26 ± 0.90	1.26 ± 0.89	1.26 ± 0.89	1.26 ± 0.90
	5%		1.23 ± 0.91	1.23 ± 0.91	1.23 ± 0.92	1.22 ± 0.92
	8%		1.21 ± 0.92	1.21 ± 0.93	1.20 ± 0.94	1.19 ± 0.94
24		1.46 ± 1.04				
	2%		1.45 ± 1.06	1.45 ± 1.05	1.44 ± 1.06	1.45 ± 1.05
	5%		1.42 ± 1.07	1.41 ± 1.07	1.41 ± 1.08	1.40 ± 1.08
	8%		1.39 ± 1.08	1.39 ± 1.09	1.38 ± 1.09	1.35 ± 1.09
32		1.58 ± 1.10				
	2%		1.57 ± 1.11	1.57 ± 1.12	1.56 ± 1.11	1.55 ± 1.11
	5%		1.52 ± 1.14	1.52 ± 1.14	1.52 ± 1.13	1.50 ± 1.14
	8%		1.49 ± 1.15	1.48 ± 1.15	1.47 ± 1.15	1.42 ± 1.14

Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area

Table 1. Fuel model and canopy data used for the wildfire simulations. The data refer to the 625 km^2 study area. FT = fuel type; FL = fuel load; FD = fuel depth; CH = average canopy height; CBD = average canopy bulk density; CBH = average canopy base height; CC = canopy cover. Treated units (TU) were considered as non-burnable fuels.

FM CODE	CORINE CODES	FT	AREA (%)	DEAD FL (t ha^{-1})	LIVE FL (t ha^{-1})	FD (cm)	CH (m)	CBD (100* kg m^{-3})	CBH (m)	CC (code)
FM21	1	AA	2.33	-	-	-	-	-	-	-
FM22	4; 5	W	0.10	-	-	-	-	-	-	-
FM23	332	R	0.01	-	-	-	-	-	-	-
FM25	211; 212; 213; 231	GR	46.06 [a]	1.2	0.0	20	0	0	0	0
FM26	241; 242; 243; 244	MA	13.26 [a]	1.2	0.0	30	0	0	0	0
FM27	221; 222; 223	VO	1.85	1.0	2.0	80	10	11	1	1
FM28	321	HP	8.68	2.5	0.0	35	0	0	0	0
FM29	333; 334	G	0.81	5.3	4.1	45	0	0	0	0
FM30	322; 323; 324	MM	9.48	15.0	12.5	135	12	14	1	1
FM31	312	CF	0.18	10.0	1.0	25	14	11	2	4
FM32	311	BF	17.19	12.0	2.0	70	12	14	2	3
FM33	313	MF	0.04	12.0	2.0	70	14	13	2	3
FM41	241, 211, 212	TU	- [a]	-	-	-	-	-	-	-

[a] These values refer to the untreated condition (NO-TREAT)

Table 2. Total area treated by Corine classes for each fuel treatment strategy and percentage of area treated at landscape scale. The Corine codes refer to annual crops with permanent crops (241), non-irrigated arable land (211), and permanently irrigated land (212). According to the 2008 Sardinia Land Use Map and focusing on areas with terrain slope below 10°, the treatable areas of the above Corine classes cover respectively 6.70%, 30.55%, and 10.15% of the whole study area

Fuel Treatment Strategy	Corine Code	Area Treated			
		NO-TREAT	2%	5%	8%
LOW					
	211	0.00%	1.05%	2.86%	4.78%
	212	0.00%	0.75%	1.57%	2.30%
	241	0.00%	0.20%	0.56%	0.91%
MED					
	211	0.00%	0.99%	2.66%	4.74%
	212	0.00%	0.83%	1.75%	2.35%
	241	0.00%	0.18%	0.59%	0.91%
LAR					
	211	0.00%	1.04%	2.74%	4.70%
	212	0.00%	0.82%	1.74%	2.41%
	241	0.00%	0.14%	0.53%	0.89%
ROAD					
	211	0.00%	1.02%	2.85%	5.27%
	212	0.00%	0.88%	1.76%	2.02%
	241	0.00%	0.10%	0.39%	0.71%