Calibration of FARSITE Fire Area Simulator in Iranian Northern Forests

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Abstract

Wildfire simulators based on empirical or physical models need to be locally calibrated and validated when used under conditions that differ from those where the simulators were originally developed. This study aims to calibrate FARSITE fire spread model considering a set of recent wildfires occurred in Northern Iran forests. Site specific fuel models in the study areas were selected by sampling the main natural vegetation type complexes and assigning standard fuel models. Overall, simulated fires presented reliable outputs that accurately replicated the observed fire perimeters and behavior. Standard fuel models of Scott and Burgan (2005) afforded better accuracy in the simulated fire perimeters than the standard fuel models of Anderson (1982). The best match between observed and modeled burned areas was observed on herbaceous fuel models. Fire modeling showed a high potential for estimating spatial variability in fire spread and behavior in the study areas. This work represents a first step in the application of fire spread modeling on Northern Iran for wildfire risk monitoring and management.

1 Introduction

Wildfires cause substantial losses of property and human lives in ecosystems in Iran as well as all around the world (Keeley and Fotheringham, 2001; Pausas et al., 2008; Banj Shafiei et al., 2010; Bracmort, 2012). Every year, about 6,000 ha of forests are affected by fires in Iran (Adab et al., 2013), and almost 7% of the area burned is located in the northern Iranian mountainous range (Banj Shafiei et al., 2010). Wildfires in Northern Iran forests are mostly caused by anthropogenic activities, as it happens in other areas (Syphard et al., 2007; Bird et al., 2008; Romero-Calcerrada et al., 2008; Martinez et al., 2009) and represent the main threat in the protected natural areas. The Northern Iran mountainous forests have a very high natural value and correspond to the main habitat for many protected, endangered or endemic animals, such as the *Iranian cheetah*, *the Persian fallow deer*, the *Persian ground jay*, the *Caucasus leopard*, *lynx*, *brown bear*, *wild boar*, *wolf*, *golden jackal*, *jungle cat*, *badger*, and plants, like the *Persian ironwood*, *Caspian beech*, the *velvet maple* and the *Caspian locust*, among many others.

As pointed out by several previous works, wildfire spread is a complex spatial and temporal dynamic process that depends on many factors such as weather, topography, fuel types and fuel moisture content (Carvalho et al., 2006; Santoni et al., 2011; Salis et al., 2014a, 2015). The ability to analyze and quantify potential wildfire likelihood, size and intensity is important for an effective wildfire management and proactive emergency response (Gu et al., 2008; Taylor et al., 2013; Ager et al., 2014a). For this reason, several surface fire spread models have been developed under many conditions in different areas around the world, particularly where wildfires are threatening forests, valued resources and human lives (Perry 1998; Pastor et al. 2003; Sullivan, 2009). These models are implemented for simulating complex physical-chemical and dynamic processes over large and spatially heterogeneous landscapes, under changing weather and fuel moisture conditions (Finney 1998; Viegas et al., 1998; Arca et al., 2007, 2009; Forthofer et al. 2007; Ager et al., 2012; Salis et al. 2015).

Fire modeling has been extensively applied in the last decades to simulate and characterize fire spread and behavior across diverse types of landscapes (Arca et al., 2007; Duguy et al., 2007; Ager et al., 2011, 2014b; Salis et al., 2013, 2014b). Many wildfire simulators have been developed since the ’90s, as SIROFIRE (Australia; Coleman and Sullivan, 1996), FARSITE (United States; Finney, 1998), PROMETHEUS (Canada; Prometheus Project Steering Committee, 1999), SPREAD (Portugal; Mendes-Lopes and Aguas, 2000) and ForeFire (France; Balbi et al., 2009), among others. FARSITE is a spatially and temporally explicit fire simulation system developed at the USDA Forest Service, Fire Sciences Laboratory of Missoula, and is still nowadays one of the most used and user friendly simulators. The simulator, which is a semi-empirical model based on Rothermel's (1972) surface fire spread model, simulates fire growth using Huygens's principle wave propagation and fire intensity is calculated from Byram's (1959) equation. FARSITE has been widely calibrated in the US and employed not only to generate spatial maps of fire spread and behavior (Finney and Ryan, 1995; Finney, 1998), but also mainly to evaluate the effects of different silvicultural prescriptions and fuel treatment options on reducing fire hazard (Stephens, 1998; Finney, 2001; Stratton, 2004; LaCroix et al., 2006; Ryu et al., 2007; Schmidt et al., 2008; Cochrane et al., 2012). The use of FARSITE simulator on areas different from those ones where the model was originally developed requires a local calibration and validation (Arca et al., 2007) using observed wildfire data, and corresponds to the primary step to then apply the simulator at larger scales (Ager et al., 2007, 2010; Stratton, 2006; Salis et al., 2013, 2014b). The reliability of FARSITE as a tool for improving wildfire analysis and landscape management options has been reported by several papers in southern Europe (Molina and Castellnou, 2002; Arca et al., 2007; Duguy et al., 2007; Mallinis et al., 2008; Glasa and Halada, 2011), as well as in New Zealand, Australia (Opperman et al., 2006) and southeast Asia (Lee et al., 2010). Nevertheless, no studies have been carried out with FARSITE in Iran and the surrounding countries of southwest Asia.

FARSITE requires a set of geospatial input data concerning topography, surface fuel models and canopy characteristics, as well as the physical parameters of the fuel bed, fuel moisture content, and weather data: The fire modeling outputs in turn, strongly depend on the resolution and reliability of the input data, especially as far as weather data and fuel models are concerned (Arca et al., 2007). Fuel models describe the physical characteristics such as fuel load, heat content, height of live and dead biomass that contribute to the size, intensity, and duration of a fire (Scott and Burgan, 2005). Although data availability increased worldwide in the recent years (e.g. http://earthexplorer.usgs.gov/), it is still very difficult to generate and update accurate fuel model maps in many regions of the world like Iran, due to the absence of specific fuel model cartography or the lack of suitable information on mapped vegetation characteristics (Pettinari et al., 2014). Several studies developed photo-guides and collections of fuel models (Anderson, 1982; Dimitrakopoulos, 2002; Scott and Burgan, 2005; Fernandes et al., 2006; Cruz and Fernandes, 2008; Rodríguez y Silva and Molina-Martínez, 2011; Cai et al., 2014; Pierce et al., 2014). Standard fuel models that fit the main local vegetation characteristics can become as input for fire spread modeling, also in combination with custom fuel models whenever available (Duguy et al., 2007; Arca et al., 2009; Boboulos et al., 2013).

In this paper, we assessed the capabilities of FARSITE in accurately replicating historical wildfire spread and behavior in northern Iran. We tested two sets of different suitable standard fuel models for the local vegetation types (Anderson, 1982; Scott and Burgan, 2005) in order to identify the ones that better replicate and fit the observed fire events. In addition, we analyzed how fire spread and behavior variables (rate of spread, fireline intensity, and flame length) were influenced by standard fuel models. This work represents the first study aiming at calibrating and validating FARSITE in northern forests of Iran. The study can improve our understanding of the potential fire spread and behavior in the southern Caspian forests and help landscape managers for fire management purposes.

2 Materials and Methods

2.1 Study area

This study was carried out considering a set of four fires that occurred in southern Caspian forests of northern Iran, specifically in the Siahkal forest area and in the Golestan National Park (GNP; Figure 1). The south Caspian forests (16,481.95 km^2) cover about 1.2% of the whole Iran (Marvi Mohadjer, 2005) and range from sea level to 2,500 m (Siadati et al., 2010). Such area presents contrasted bioclimatic differences in comparison with the central and southern parts of the country, which are characterized by xeric weather conditions.

The Siahkal forest area is located in northern Iran, occupies 1,050 km^2, and presents a very high altitudinal range from the lowest areas at 10 m a.s.l. up to the 2500 m a.s.l. in the highest mountains (Figure 1). The annual precipitation ranges from 600 mm in the southern part to 2,000 mm in the northern and highest mountains, and most of the annual rainfall occurs in autumn. Air relative humidity exceeding 80% is responsible of frequent fogs at higher altitudes. The average annual temperature is 16°C and average summer temperature is 25°C. Average minimum temperatures of the coldest month are commonly higher than 0°C (Akhani et al., 2010). The forests, which form a long and narrow vegetation belt on the northward slopes of the Alborz Mountains, constitute the main representative of the Euro-Siberian flora in Iran (Djamali et al., 2009). The highest proportion (46%) of the Siahkal area is covered by forests, which are dominated by temperate broad-leaved deciduous trees and are characterized by many thermophilous Tertiary relict species such as *Zelkova carpinifolia*, *Parrotia persica*, *Pterocarya fraxinifolia*, *Quercus castaneifolia* and Asian subtropical trees such as *Diospyros lotus*, *Gleditsiacaspica*, *Danae racemosa* and *Albizzia julibrissin* (Akhani, 1998; Akhani and Ziegler, 2002; Leestmans, 2005; Leroy and Arpe, 2007).

The Golestan National Park (GNP) is situated in northeast Iran, and covers about 920 km^2 of land (Figure 1). The National Park is located in a transitional position between the sub-humid south

Caspian region and the semi-arid zones of central and east-central Iranian Plateau. The GNP ranges from 450 to 2,400 m above sea level. The wet air masses from the Caspian Sea are blocked by the high mountain ranges, which create particular microclimatic conditions, with annual precipitation ranging from 150 mm in the southeast up to more than 1,000 mm in some central parts of the GNP (Akhani, 1998). The mean annual temperature ranges between 11.5°C and 17.5°C and average summer temperature is 28°C. The park exhibits a diverse mosaic of vegetation units, including the Hyrcanian low to high altitude mesophytic forests, shrublands, open and closed scrub sometimes mixed with C4-grasslands, Juniperus woodlands, mountain steppes and meadows, Artemisia and Artemisia–Stipa steppes and different transitional and halophilous communities (Table 1; Akhani, 1998; Akhani and Ziegler, 2002).

2.2 Wildfire history

In the period 2000-2011, Northern Iran experienced annually on average about 400 fires that burned around 2,000 hectares. Large and extreme fires in the study areas are commonly linked to drought conditions, heat waves, strong winds and fine dead fuel accumulation (Mirdeylami et al., 2014). As many as 90% of the fires in the northern Iran and study areas are caused by humans (Sarkargar Ardakani, 2007; Zarekar et al., 2013; Mirdeylami et al., 2014). Fires in northern Iran commonly occur during the short drought season in autumn, characterized by hot and dry winds that desiccate the forest understory. These conditions mostly lead to low-intensity surface fires, which rarely exceed 10-30 cm in f1ame height (Adel et al., 2012).

Wildfires in the Golestan National Park, as well as in the Siahkal forests, are distributed from June to December, with two peaks of the number fires and burned area in June-July and November-December (Figure 2). Although observed annual fire number and burned area in the

Golestan National Park and the Siahkal forests present high inter-annual variability during the period 2000-2011, the hardest wildfire campaigns correspond to the latest years, and especially to 2010 (Figure 3). During the period 2000-2011, the Siahkal area experienced on average about 13 fires per year and about 60 hectares burned (Department of Forestry, Natural Resources Office, Guilan, Iran; Figure 3). Approximately 85% of the fires in Siahkal burned less than 10 ha; a small amount of fires (about 15%) is responsible of half of the area burned (Figure 4) and no fires larger than 100 ha were observed in the studied period. On the other hand, in the Golestan National Park, in the period 2000-2011, ~12 fires per year have been recorded on average, with ~200 ha burned (Figure 2). In this area, the largest fires (>100 ha) accounted for about 15% of the fires, and were responsible of almost 75% of the total area burned (Figure 4). The largest wildfire in the Golestan National Park (Cheshme Sardar fire event) was observed in on 15 November 2010 and burned approximately an area of about 900 ha.

2.3 Case studies

Four wildfires that affected the study areas during the 2010 and 2011 fire seasons were selected as case studies: Toshi and Malekroud fires in Siahkal forest, and YekeBermagh and Gharangi fires in the Golestan National Park (Figure 1). The exact location, main types and dominant species of vegetation together with fire data for the different case studies are summarized in the Table 1. For all case studies, ignition locations coordinates were determined from fire reports (pers. comm., 2011, 2012) and interviews to forest rangers, firefighters and Park managers, and burned area perimeters were recorded after the fire events using a Global Positioning System (GPS).

The Toshi wildfire occurred near the village of Toshi (lat. 37º 11´ N, long. 49º 88´ E) on August 2010, and the 25 hour fire event burned 34 ha (Figure 5; Table 1) corresponding to mixed dense woodland (~16.4 ha), grasslands (~13.4 ha) and grass-shrublands (~4.7 ha). The ignition point was located near a steep slope, in an agricultural area (Figure 5). The weather was characterized by maximum temperature of 35°C, average relative humidity of 50%, and northeast winds (Table 2). The fire spread towards south-east, driven by the wind and the topographic conditions.

The Malekroud wildfire occurred near the town of Malekroud (lat. 37º 03´ N, long. 49º 84´ E), on December 2010, and burned approximately 24 ha covered by heterogeneous structural characteristic mature forest in a low elevation area (Figure 5; Table 1). The fire started near a road along the southern border of the fire perimeter. It was extinguished by the Forest firefighters after 17 hours near a road, along the northern border of the fire perimeter (Figure 5). The day characterized by moderate maximum temperature (~25°C), average relative humidity of 58% and southern winds. The fire was driven towards north by the mild slope and the wind.

The YekeBermagh wildfire occurred in the southern part of the Golestan National Park (lat. 37º 22´ N, long. 56º 03´ E) on July 2011 (Figure 5; Table 1). The northern part of the Yeke Bermagh area is characterized by a flat topography, while the southern part has a more complex and steep terrain with high spatial and temporal variability in wind speed and direction. Most of the 60 ha burned were covered by grasslands. Juniperus woodlands and grass-shrublands composed by montane *Juniperus excelsa* in steep slopes and subalpine *Juniperus communis* on exposed high slopes (Akhani, 1998) were also affected by the fire. The day of the fire the weather was hot (31°C maximum temperature) and dry (21% relative humidity). Fire spread was driven by the topography and the southwestern winds.

The Gharangi wildfire occurred on March 2011, in the southern part of the Golestan National Park (lat. 37º 21´ N, long. 56º 02´ E), and burned about 10 ha (Figure 5; Table 1) of dense-mixed woodland. The area presents a mountainous orography with an altitude range between 1,200 and 2,160 m a.s.l. The fire weather was mild, with maximum air temperature of 17°C and average relative humidity of 49%. The fire spread towards north and north-east driven by south-west winds. The fire intensity was low due to the shielding effect of the dense and closed canopy.

2.4 Fuel mapping and fuel model assignments

Fuel model and canopy characteristic maps for the study areas were produced by field sampling on the vegetation complexes existing in the 1:25,000 land-cover maps of 2004 (Department of Forestry, Natural Resources Office, Guilan, and Department of Environment, Golestan, Iran) due to the lack of information on forest and shrubs cover types that could allow on standard fuel model assignment. Furthermore, with the geo-referenced data derived from field sampling in the study areas we generated fuel model maps and photo guides improving the initial 1:25,000 land-cover maps, and creating finer scale vegetation layers. The field samplings were conducted following the Line Intersect Sampling (LIS; Marshall et al., 2000; 2003) method, with the objective of measuring the surface fuel model parameters and canopy characteristics.

On the whole, according to the topography in the study areas and the vegetation types, 21 line transects with a distance of 150 m in Siahkal forests and 25 line transects with a distance of 100 m in the GNP were used to respectively georeference 188 and 250 sampling plots (Table 3). Considering the spatial distribution and the coverage degree for the different species within the different vegetation types, 1 m × 1 m size square sampling plots were used for herbaceous fuel types and 10 m × 10 m size square sampling plots in shrubby and forested vegetation types. We measured species composition, fuelbed depth, litter type (conifer or broadleaf), herbaceous cover, shrub cover, canopy cover, bare ground, as well as the vegetation photographs (Table 3). Visual estimations were used to assign a canopy cover class (<1%, 1-5%, 6-10%, 11-25%, 26-50%, 51-75% and 76-100%) in every plot.

In this study, standard fuel models (Anderson, 1982; Scott and Burgan 2005) were assigned to the existing vegetation and land use land-covers types based on their similarities in structural characteristics (Figure 5; Table 3; Figure 6). The grass-dominated standard fuel models used were GR3, GR4, GR5, GR6, GR7 and FM3. GS1, GS2, GS3, GS4, FM5 and FM6 fuel models were considered for the vegetation presenting a mixture of grass and shrub components. SH1, SH2, FM5 and FM6 fuel models were assigned to areas with sparse grassland among shrubby patches covering at least the 50% of the surface. In forested areas with grass-shrub and litter mixed understory, TU1, TU2, TU3, TU5, FM8, FM9 and FM10 fuel models were used, whereas TL2, TL6, TL8 and TL9 were used for woody fuels beneath forest canopies. FM9 and FM10 covered timber litter, hardwood litter and litter and understory. Non burnable (NB) fuel models were assigned for roads, buildings, urban areas, ploughed agricultural lands, water bodies and bare ground, and in that case the geospatial information was gathered from the 1:25,000 digital topographic maps (National Cartographic Centre of Iran).

2.5 Input data for fire simulations

Fire spread simulation systems require spatial grids of topography (slope, aspect and elevation), surface fuels (fuel model) and fuels canopy characteristics (stand height, crown base height, crown bulk density, canopy cover) as basic inputs for the simulations. These data layers were assembled in a landscape file (LCP), with 10 m resolution. Topography layers were derived from the digital elevation model (DEM 10 m resolution; National Cartographic Centre of Iran, NCC) for each study area. As previously described, surface fuels layers were prepared based on land cover maps and field sampling.

Weather data of the day of the fire, corresponding to hourly air temperature, relative humidity, rainfall, wind speed and direction were collected from the nearest weather stations to the wildfire case studies (Figure 5 and Table 2).

Initial fuel moisture content (FMC) for the 1-h, 10-h and 100-h dead fuels (Table 3) was determined following the methodology proposed by Rothermel (1983; Annex A1). With this method, we estimated the fine dead FMC for each case study, and then we derived 10 hr and 100 hr dead moisture by adding 2% and 4% respectively to the 1 hr dead FMC (Hardison, 2003). The live herbaceous and woody FMC values (Table 3) were estimated from literature data (Arca et al., 2007; Sağlam et al., 2008; Chuvieco et al., 2011) and mostly from field observations.

2.6 FARSITE simulations

Fire simulations were run at 10 m of resolution, using different combinations of standard fuel models (Anderson, 1982; Scott and Burgan, 2005) for the main fuel types (grasslands, grass-shrublands, shrublands, timber understory, and timber litter) affected during wildfire events (Table 4). For all simulations and fuel models, the adjustment factor for the fire spread rate was set at 1.0. Suppression activities were not considered in the simulations doe to the lack of information, as well as spot and crown fires, since both were not observed in the case studies presented in this paper. Ignition location and fire spread duration used as inputs for each case study are provided in Table 1. Vector files of the simulated fire perimeters and gridded data of simulated rate of spread (ROS, m min^{-1}), fireline intensity (FLI, kW m^{-1}) and flame length (FML, m) were exported and analyzed in GIS environment.

2.7 Statistical analysis

The influence of fuel models on the accuracy of simulated fire spread and behavior was assessed for all the case studies. An error matrix between observed and simulated fire perimeters was calculated to define the frequency of each case (presence/absence of burned areas). Sorensen's coefficient (SC; Legendre and Legendre, 1998) and Cohen's Kappa coefficient (K; Congalton, 1991) were used as measures of the spatial accuracy of the extent of the simulated fire spread (Arca et al., 2007; Salis, 2008).

Sorensen's coefficient (SC) was used as indicator of the exclusive association between observed and simulated burned areas. SC values were calculated as follows:

$$SC = \frac{2a}{2a+b+c}$$

Where *a* is the number of cells coded as burned in both observed and simulated data (burned area agreement), *b* is the number of cells coded as burned in the simulation and unburned in the observation (modeling overestimation), and *c* is the number of cells coded as unburned in the simulation and burned in the observation (modeling underestimation; Arca et al., 2007).

Kappa statistics (K) computes the frequency with which simulated area agrees with observed area; with an adjustment that takes into account agreement by chance (Filippi et al., 2014). K values were calculated as follows:

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+}x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+}x_{+i})}$$

Where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively, and N is the total number of observations. Both K and SC coefficient values typically range between zero and one, with values close to one indicating very high spatial agreement between simulated and observed fire perimeters (Arca et al., 2007).

Moreover, the Zonal Statistics tool of ArcGis 10 was used to analyze and summarize the fire behavior data (ROS, FLI and FML) for each fuel model.

3 Results

3.1 Fire simulation accuracy

For all the case studies, the simulated burned areas were compared with the observed fire perimeters (Figure 7 and Tables 4 and 5). Overall, the statistics showed that FARSITE performances with the highest values for K and SC coefficients and therefore the scenarios that better replicate the observed fires, were obtained for all the case studies using the standard fuel models of Scott and Burgan (2005), with the exception of the simulation II of Malekroud, where the standard fuel model (FM9) of Anderson (1982) showed the best accuracy in replicating the fire perimeter (Table 4).

In the Toshi fire event, the best results were obtained in the simulation III (Figure 7a, Table 4), where about 30.1 ha of the final fire area coincided with the observed fire size, while 4.1 ha and 5.5 ha were respectively underestimated and overestimated by FARSITE. As previously pointed out, the best values of SC and K coefficients were obtained in the simulation III (SC=0.86, K=0.82; Table 4), whereas the other simulations presented lower accuracies, with SC values ranging from 0.48 to 0.83, and K values from 0.45 to 0.81. The best performance for Toshi wildfire, regarding the standard fuel models used, was obtained by the GR6 fuel model (SC=0.92, K=0.87; Table 5) for grasslands and the worst was observed for the TU3 fuel model (SC=0.75, K=0.73; Table 5).

The simulation II of Malekroud wildfire event (Figure 7b, Table 4) replicated well the observed fire event, with an agreement between the observed and simulated fire area of about 20.6 ha and FARSITE underestimation and overestimation of 3.5 ha and 5.5 ha respectively. The statistical analysis showed that the FM9 fuel model in simulation II provided the highest SC and K values (SC=0.85; K=0.82; Table 5), while the other simulations using TL6 and FM10 fuel models gave SC values ranging from 0.73 and 0.79 and K values ranging from 0.71 and 0.75 (Table 4). Focusing on single fuel models, the FM9 fuel model in Toshi case study provided the worst accuracy performance (SC=0.48; K=0.45; Table 4).

In the simulation VI of the YekeBermagh case study (Figure 7c, Table 4), the simulated fire area was characterized by an overestimation of 30.7 ha, mainly in the right back-flank of the fire spread. The agreement between the simulated and observed fire area was about 46.8 ha, while 11.2 ha of the fire area were underestimated (Table 4). The statistical test showed that in the simulation VI the GR4 fuel model provided the best SC and K values (SC=0.82, K=0.81; Table 5), while the worst performances were provided by the FM3 fuel model in the simulation VII (SC=0.13, K=0.12; Table 4), due to the wide underestimation of the area burned. The large underestimation was also confirmed for the FM5 and FM6 fuel models (Table 4).

In the simulation I of Gharangi wildfire event (Figure 7d, Table 4), about 7.5 ha of the observed fire area were correctly simulated as burned area by FARSITE. The extent of the underestimation by the simulation was approximately 2.6 ha, and the overestimation 2.2 ha. The best agreement between simulated and observed fire was linked to TL9 fuel model (SC=0.91; K=0.91; Table 5), which was characterized by small overestimation and underestimation of the FARSITE perimeter.

Comparing the standard fuel models associated to the best simulations of FARSITE for each case study, the higher SC and K values were obtained using the GR6 grassland model in the simulation III of the Toshi fire (SC=0.92; K=0.87; Table 5) and the TL9 timber model in the simulation I of the Gharangi fire (SC=0.91, K=0.91; Table 5). The worst performances were provided by the model TU1 in the simulation I of Gharangi fire event (SC=0.47; K=0.45; Table 5). On the whole, GR6, TU2, TU5 and TL9 fuel models replicated well the observed area burned (SC $\geq$0.90 and K$\geq$0.82; Table 5).

3.2 Fuel models and fire behavior

Due to differences in fuel models characteristics, topography and weather conditions, the simulations revealed diverse potential fire behavior. Surface fire rate of spread (ROS), fireline intensity (FLI), and flame length (FML) were analyzed for each of the fuel models used in the four case studies (Figure 8 and Table 5). The fire simulation outputs showed complex patterns that were generally related to the dominant fuel types and to topography.

Overall, for the case studies presented the average wind speed conditions ranged from 14 to 23 km h^{-1} (Table 2), and for this reason the fires spread slowly and the average ROS was between 0.5 to 2.6 m min^{-1} (Table 5), with the lowest values observed in the Gharangi wildfire.

The highest values of simulated ROS were observed with tall and dense grasslands and sparse shrubland vegetation in Toshi and YekeBermagh case studies (Table 5). The grasslands presented the fastest ROS, which varied from 0.05 to10.84 m min^{-1} (Table 5) depending on topography; the shrublands showed a ROS ranging from 0.05 to 8.06 m min^{-1} (Table 5). The lowest ROS (<1 m min^{-1}; Table 5) were obtained for the areas covered by mixed hardwood forest (TU1) and pure hardwood forest (TL6) in Gharangi wildfire. In woodlands, modeled fire ROS was very slow due to the high fuel compactness and the relatively high moisture content: This explains the ROS values 2~3 times lower than in grassland fuel types (Table 5).

As well as for ROS, relevant differences in terms of FLI were identified between grasslands and other vegetations types. The grass fuel models presented the highest FLI (>350 kW m^{-1}; Table 5). The higher FLI values were also associated to shrubland fuel models (SH1 and SH2; >250 kW m^{-1}; Table 5) in YekeBermagh wildfire case study. Moreover, in woodlands the FML was short (<1 m; Table 5) compared to other vegetation types, while the longest flame values were obtained for tall grasslands (>1 m; Table 5).

4 Discussion

The propagation of a wildfire depends on complex interaction among terrain, fuel types, weather conditions, fire suppression, and the heat released by the fire environment (Viegas et al., 1998; Forthofer and Butler, 2007; Fernandes, 2009; Lee et al., 2010; Sharples et al., 2012; Cardil et al., 2013). The use of fire spread models can help understanding the expected behavior of hypothetical fires and improve logistics decision-making and thereby improve the safety of firefighters. Nevertheless, fire spread model adoption and application in a given landscape should be preceded by a calibration process, as well as validation efforts that demonstrate that the model outcomes describe well an event with acceptable errors (Stratton, 2006; Arca et al., 2007; Randall et al., 2007; Alexander and Cruz, 2013). In fact, modeling fires is difficult due to a myriad of causes, including spatial heterogeneity in environmental factors and the variable effects of fire suppression over the range of fire sizes (Taylor et al., 2013). On the other hand, calibration and validation of fire simulations in general is also made difficult by the multiple sources of errors that are confounded with the error of the model itself. These sources may include an insufficient accuracy of spatial fuels information, the distance between the weather station locations to the area where the fire occurred, and mapping of fire perimeters, errors from the user who runs the models like determining the model parameters (Finney et al., 2011). Many studies have shown that the use of both wind field data and appropriate custom fuel models are essential to obtain reasonable simulations of fire spread and behavior (Arca et al., 2007; Salis, 2008; Forthofer et al., 2007). Although the resolution of the spatial input data for FARSITE was 10 m, the obtained output resolution was limited in some terms by the original land use land-cover map and the digital elevation model data source 1:25000 original resolution.

As the obtained outcomes have shown in the current and other previous works (Stratton, 2009; Cochrane et al., 2012), FARSITE results in an accurate and reliable single fire event simulator able to replicate observed wildfires at high resolution (20 m or finer resolutions). However, although FARSITE has also been used at landscape scale for several fire modeling and fire likelihood analysis (Bar Massada et al., 2011), other simulators as FlamMap and its command implementation of Randig (also using Rothermel's fire spread model; Finney et al., 2006) present some advantages respect to FARSITE when working at large scales (thousands of hectares and square kilometers) and huge amount of fire ignitions (several thousand fire modeling).

The goal of this manuscript was to assess the capabilities of FARSITE in replicating wildfire spread and behavior in northern Iran, where the number of scientific studies and projects on fire behavior and spread are still limited. Plenty of studies on these topics have been carried out in the United States, southern Europe and other Mediterranean areas, and local site-specific fuel models have been developed and widely employed in fire modeling (Finney, 1998, 2003; Finney et al., 2006; Scott and Burgan, 2005; Santoni and Balbi, 1998; Arca et al., 2007, 2009; Fernandes et al., 2006; Salis et al., 2010, 2013, 2014b). Albeit standard fuel models should not be applied uncritically to ecosystems outside of North America, this study showed that some standard fuel models accurately replicated the observed burned areas in our study areas.

Concerning the simulation accuracy, FARSITE overestimations were expected and observed for all case studies (especially in YekeBermagh), since suppression activities were not considered in the simulations. The good spatial agreement between the observed and simulated fire perimeters, as measured by SC and K coefficients, resulted in values higher than 0.69 for SC and 0.68 for K, considering all case studies and the most accurate FARSITE simulations. In more detail, the best FARSITE simulations ranged from 0.69 to 0.86, in terms of SC, and from 0.68 to 0.82, in terms of K (Table 4).

Overall, the simulations performed using the standard fuel models by Scott and Burgan (2005) provided better results than the Anderson fuel models (1982) in replicating the observed fire area, with the exception of the Malekroud case study (SC= 0.81; K= 0.78; Table 4). Among the fuel models, the best match between observed and modeled area burned was observed in tall grasslands (GR6; Scott and Burgan, 2005; Table 5), although also other fuel models (TU2, TU5 and TL9) provided very high accuracy, with SC $\geq$0.90 and K$\geq$0.82 (Table 5).

Simulation outputs of ROS, FLI and FML showed average values under suppression capabilities for fire extinction crews and equipment (Andrews et al., 2011; Table 5), for a number of fuel models. As expected, and in agreement with the information provided by the Forest Brigades of the study areas, the highest spread rate and intensity values for the selected case studies were associated to grass and shrubs fuel models, which have high load and height. These results are in agreement with several studies conducted to estimate fire behavior variables, such as Arca et al (2007) and White et al (2013). Specifically, the areas dominated by tall grass (GR6 and GR7) exhibited the highest rate of spread (ROS>5 m min^{-1}; Table 5), with moderate flame length (FML<2.5 m; Table 5): Such fire behavior created strong difficulties for fire suppression mostly because of the high rate of spread, rather than the fire intensity. The limitations in effectively control fire spread rates were amplified in the areas where the terrain steepness was aligned with wind direction (e.g., Toshi wildfire, Figure 8).

On the other hand, in timber litter and timber understory fuel models, the dead and live fuel moisture content is commonly higher than in open areas, the likelihood of fire ignition is much lower, and the spread rate and intensity do not present relevant complications for fire extinction if the fire spreads as surface fire, as observed in the case studies selected.

5 Conclusions

There are relevant effects of the fuel models characteristics on simulated fire spread and behavior. FARSITE simulations performed for the fires events that affected northern Iranian forests highlighted different simulated fire perimeters, final size, rate of spread and intensity. Overall, in both study areas, specific USDA standard fuel models were able to represent local fuel types and characteristics, which were defined and mapped combining field sampling activities and 1:25.000 land cover maps. The best match between observed and simulated area burned was observed on grasslands fuel types.

Overall, fire modeling has high potential for estimating spatial variability in fire spread and behavior in the study areas. This work represents a first step in the application of fire spread modeling in Northern Iran for wildfire risk monitoring and management. Quantifying potential fire behavior, exposure and risk in Northern Iran, represents a challenging point for researchers due to the limited availability of data about local fuels and fires, and a huge work of field sampling and mapping is needed.

Furthermore, this work provides useful methodologies that can be replicated in the southern Caspian forests to characterize fire likelihood and intensity and will increase local awareness of the risks posed by fire spreading in such forest ecosystems. Nevertheless, there were some limitations for the study such as the insufficiency or lack of custom fuel models, high resolution wind field data and details on observed fire propagation that may have affected the accuracy of the results. Further efforts should be carried out to investigate crown fire behavior in the study area, although in our cases the fires only affected surface fuels, as well as to simulate the spatial variation of wind speed and direction, to improve the reclassification of vegetation types in standard fuel models, and to complete the field sampling in order to produce custom fuel models and more precise photo-guides for northern Iran.

Acknowledgements

The Iranian Forests, Range and Watershed Management Organization and the Iranian Department of Environment are also thanked for the permission and logistic supports during the field works. We wish to acknowledge the unrelenting help of the Directors of the Department of Natural Resources in Siahkal and the Golestan National Park and the park rangers and firefighters during the field excursions. The authors also acknowledge financial support from Natural Sciences and Engineering Research Council of Canada (NSERC).

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Table 1. Case study sites description.

Site	Siahkal		Golestan National Park	
Wildfire	Toshi	Malekroud	YekeBermagh	Gharangi
Latitude of the ignition point	37º 11’	37º 03’	37º 22’	37º 21’
Longitude of the ignition point	49º 88’	49º 84’	56º 03’	56º 02’
Elevation (m) of the ignition point	210	120	2080	1370
Main fuel types affected by the fire	grasslands, grass-shrublands and timber understory	timber litter	Grasslands and grass-shrublands	timber understory and timber litter
Dominant plant species	*Carpinus betulus* L., *Quercus castaneifolia* C.A.Mey., *Alnus subcordata* C.A.Mey., *Parrotia persica* C.A.Mey., *Acer insigne var. velutinum* Boiss., *Asperula odorata* L., *Euphorbia helioscopia* L., *Ilex aquifolium* L.	*Acer insigne var. velutinum* Boiss., *Quercus castaneifolia* C.A.Mey., *Fagus orientalis* C.A.Mey., *Populus caspica* C.A.Mey., *Tilia begonifolia* Stev., *Pyrus commonis* L., *Buxus hyrcanus* Pojark., *Mespilus germanica* L., *Smilax excelsa* L., *Hypricum androsenum* L.	*Festuca drymeia* Mert. & Koch., *Artemisia sieberi* Besser., *Astragalus jolderensis* B.Fedtsch., *Poa bulbosa* L., *Thymus kotschyanus* Boiss. & Hohen., *Stipa holosericea* Trin., *Juniperus excelsa* M. Bieb., *Juniperus communis* L.	*Quercus castaneifolia* C.A.Mey., *Carpinus betulus* L., *Carpinus orientalis* Mill., *Acer cappadocicum* Gled., *Mespilus germanica* L., *Euphorbia amygdaloides* L., *Viola alba* Besser., *Primula heterochroma* Stapf., *Galium odoratum* (L.) Scop.
Fire ignition (date and hour)	14 August 2010 (16.00)	17 December 2010 (17.00)	15 July 2011 (11.00)	28 March 2011 (14.00)
Fire extinguishment (date and hour)	15 August 2010 (17.00)	18 December 2010 (08.00)	15 July 2011 (21.00)	28 March 2011 (21.00)
Burned area (ha)	34.18	24.05	58.06	10.04

Table 2. Overview of the weather conditions observed during the wildfire days in the closest weather stations.

Site	Siahkal*		Golestan National Park **	
Wildfires	Toshi	Malekroud	YekeBermagh	Gharangi
Maximum Temperature (°C)	35	25	31	17
Minimum Temperature (°C)	20	7	14	5
Precipitation (mm)	0	0	0	0
Maximum Wind Speed (km h^{-1})	28.8	32.4	25.2	18.0
Average Wind Speed (km h^{-1})	21.6	23.4	21.6	14.4
Average Wind Direction	NE	S	SW	SW
Average Air Relative Humidity (%)	50	58	21	49

* Lahijan Station (Altitude -2 m a.s.l.; lat. 37º 11´, long. 50º 00´), located 15 km away from the northeast of Siahkal forest area.

** Robate-GharehBil automatic weather station (Altitude 1282 m a.s.l.; lat. 37º 21´, long. 56º 19´), located 20 km away from the east boundaries of GNP.

Table 3. Vegetation types and respective fuel models and fuel moisture parameters used in FARSITE simulations. (FMC= fuel moisture content; 1-hr= 0-0.6 cm diameter particle size class; 10-hr= 0.6-2.5 cm diameter particle size class; 100-hr= 2.5-7.6 cm diameter particle size class; LH= live herbaceous; LW= live woody).

			Surface Fuel Model data					Assigned Fuel Models		FMC (%) Dead Fuel (%)			FMC (%) Live Fuel (%)	
Wildfire	Vegetation Type	Number of Sample Plots	Fuel Bed Depth (cm)	Litter Type	Herbaceous Cover (%)	Shrub Cover (%)	Canopy Cover (%)	Scott and Burgan (2005)	Anderson (1982)	1-hr	10-hr	100-hr	LH	LW
Toshi	Grassland	55	65.5	-	75	-	30	GR3, GR5, GR6	FM3	11	12	14	0	0
	Grass-Shrubland	27	82	broadleaf	40	40	20	GS3, GS4	FM5, FM6	11	12	14	0	70
	Natural Mixed Forest	41	4.5	broadleaf	25	10	80	TU2, TU3	FM9, FM10	11	12	14	0	100
Malekroud	Mixed and Pure Plantation	65	5	conifer and broadleaf	15	10	75	TL2, TL6, TL8, TL9	FM9, FM10	14	15	17	50	100
YekeBermagh	Grassland	130	45	-	85	-	50	GR4, GR7	FM3	5	6	8	0	0
	Grass-Shrubland	38	54.5	conifer	30	40	10	GS1, GS2	FM5, FM6	5	6	8	0	60
	Shrubland	35	75.5	conifer	35	50	45	SH1, SH2	FM5, FM6	5	6	8	0	70
Gharangi	Natural Mixed Forest	27	3.5	broadleaf	10	5	80	TU1, TU5	FM8, FM10	13	14	16	75	100
	Natural Pure Forest	20	4	broadleaf	15	5	75	TL2, TL6, TL9	FM9, FM10	13	14	16	75	100

Table 4. Statistical evaluation of FARSITE performance for different combinations of standard fuel models. The Sorensen's coefficient (SC) and the Cohen's kappa coefficient (K), derived from the error matrix; were used for such purpose. (a) observed-modeled burned area agreement (ha); (b) simulation overestimation (ha); (c) simulation underestimation (ha).

Site (observed fire size in ha)	Simulation Number	Fuel Model code	SC	K	a (ha)	b (ha)	c (ha)
Toshi (34.18 ha)	I	(GR3, GS3, TU2, TU3)	0.70	0.70	18.78	0.41	15.40
	II	(GR5, GS3, TU2, TU3)	0.76	0.75	22.35	2.13	11.83
	III	**(GR6, GS3, TU2, TU3)**	**0.86**	**0.82**	**30.06**	**5.51**	**4.12**
	IV	(GR6, GS4, TU2, TU3)	0.83	0.81	28.14	5.78	6.04
	V	(FM3, GS3, TU2, TU3)	0.82	0.79	27.08	4.53	7.10
	VI	(GR6, FM5, TU2, TU3)	0.77	0.74	23.10	2.44	11.08
	VII	(GR6, GS3, FM10, TU3)	0.71	0.69	20.45	2.73	13.73
	VIII	(GR6, GS3, TU2, FM10)	0.73	0.71	22.18	4.51	12.00
	IX	(FM3, FM6, FM10)	0.68	0.67	19.36	3.51	14.82
	X	(GR6, GS3, FM9, TU3)	0.48	0.45	11.36	1.65	22.82
Malekroud (24.05 ha)	I	(TL6, TL9)	0.76	0.73	17.18	4.13	6.87
	II	**(FM9, TL9)**	**0.81**	**0.78**	**20.57**	**5.51**	**3.48**
	III	(TL6, FM9)	0.75	0.73	16.95	4.01	7.10
	IV	(TL6, FM10)	0.73	0.71	15.84	3.48	8.21
	V	(FM9)	0.79	0.75	19.45	5.60	4.60
YekeBermagh (58.06 ha)	I	(GR4, GS1, GS2)	0.26	0.22	58.06	326.48	0.00
	II	(GR7, GS1, GS2)	0.24	0.20	58.06	358.90	0.00
	III	(FM3, GS1, GS2)	0.41	0.38	58.06	165.91	0.00
	IV	(GR4, SH1, GS1)	0.50	0.49	54.14	106.13	3.92
	V	(GR7, SH1, GS1)	0.46	0.46	57.34	133.27	0.72
	VI	**(GR4, SH1, SH2)**	**0.69**	**0.68**	**46.84**	**30.75**	**11.22**
	VII	(FM3, SH1, SH2)	0.13	0.12	4.26	3.27	53.80
	VIII	(FM3, GS1, GS2)	0.66	0.63	51.43	45.86	6.63
	IX	(FM3, FM5, FM6)	0.67	0.66	50.14	41.67	7.92
	X	(GR4, FM5, FM6)	0.27	0.23	58.06	308.65	0.00
Gharangi (10.04 ha)	**I**	**(TU1, TU5, TL6, TL9)**	**0.76**	**0.75**	**7.48**	**2.23**	**2.56**
	II	(FM8, TU5, TL6, TL9)	0.67	0.65	7.50	4.81	2.54
	III	(FM10, TU5, TL6, TL9)	0.57	0.56	8.44	11.30	1.60
	IV	(TU1, FM10, TL6, TL9)	0.72	0.69	6.93	2.18	3.11
	V	(TU1, TU5, FM9, TL9)	0.71	0.68	6.87	2.24	3.17
	VI	(TU1, TU5, TL6, FM10)	0.70	0.68	6.63	2.19	3.41
	VII	(FM8, FM9, FM10)	0.70	0.68	6.79	2.54	3.25

Table 5. Statistical evaluation of the best FARSITE simulations (III for Toshi, II for Malekroud, VI for YekeBermagh and I for Gharangi; Table 4) for each case study. Mean values (±SE) of the simulated ROS, FLI and FML are also reported. (SC= Sorensen's coefficient value; K= Cohen's kappa coefficient value; a= burned area agreement; b= FARSITE overestimation; c= FARSITE underestimation; ROS= rate of spread; FLI= fire line intensity; FML= flame length).

Site and the best simulation	Fuel Model	SC	K	a (ha)	b (ha)	c (ha)	Observed fire size (ha)	Simulated fire size (ha)	ROS (m min^{-1})	FLI (kW m^{-1})	FML (m)
Toshi (III)	106 GR6	0.92	0.87	12.87	2.11	0.27	13.14	14.98	3.94±2.49	655.62±418.38	1.44±0.46
	123 GS3	0.87	0.85	3.98	0.43	0.70	4.68	4.41	1.20±0.38	169.26±63.80	0.80±0.16
	162 TU2	0.90	0.82	6.28	0.07	1.35	7.63	6.35	0.58±0.31	46.44±41.72	0.42±0.14
	163 TU3	0.75	0.73	6.93	2.90	1.80	8.73	9.83	1.61±1.55	239.38±261.60	0.88±0.42
	Total	**0.86**	**0.82**	**30.06**	**5.51**	**4.12**	**34.18**	**35.57**	**2.27±2.23**	**357.65±383.74**	**1.01±0.53**
Malekroud (II)	FM9	0.85	0.82	16.12	3.19	2.80	18.92	19.31	1.76±0.78	126.35±56.01	0.69±0.14
	189 TL9	0.77	0.74	4.45	2.32	0.68	5.13	6.77	1.62±0.75	262.96±155.09	0.95±0.30
	Total	**0.81**	**0.78**	**20.57**	**5.51**	**3.48**	**24.05**	**29.56**	**1.72±0.78**	**160.63±108.19**	**0.76±0.23**
YekeBermagh (VI)	104 GR4	0.82	0.81	42.05	19.93	5.82	47.87	61.98	2.60±1.28	341.26±255.52	1.01±0.39
	141 SH1	0.75	0.72	3.29	5.39	2.52	5.81	8.68	2.83±1.09	266.89±113.11	0.95±0.19
	142 SH2	0.50	0.50	1.50	5.43	2.88	4.38	6.93	1.49±1.63	248.52±234.96	0.58±0.56
	Total	**0.69**	**0.68**	**46.84**	**30.75**	**11.22**	**58.06**	**77.59**	**2.61±1.36**	**277.86±416.89**	**0.97±0.70**
Gharangi (I)	161 TU1	0.47	0.45	0.90	0.82	2.18	3.08	1.72	0.32±0.29	85.55±118.41	0.45±0.36
	165 TU5	0.90	0.85	3.52	0.52	0.30	3.82	4.04	0.67±0.24	205.75±115.23	0.86±0.22
	186 TL6	0.77	0.77	0.95	0.49	0.08	1.03	1.44	0.23±0.04	23.99±24.38	0.32±0.09
	189 TL9	0.91	0.91	2.11	0.40	0	2.11	2.51	0.63±0.19	149.43±83.11	0.74±0.20
	Total	**0.76**	**0.75**	**7.48**	**2.23**	**2.56**	**10.04**	**9.71**	**0.53±0.28**	**184.43±147.94**	**0.76±0.37**

Annex

A 1. The method used for calculating initial dead fuel moisture content (FMC) based on Rothermel (1983) in wildfire case studies

	Variable	Wildfire			
		Toshi	Malekroud	YekeBermagh	Gharangi
1	Ambient temperature	28	16	24	10
2	Relative Humidity	50	58	21	49
3	Reference number for fuel moisture (Rothermel, 1983, p.17)	8	8	4	8
4	Month	August	December	July	March
5	Table to be used (Rothermel, 1983, p.18)	C	D	B	C
6	Exposed[1] or shaded	Exposed	Exposed	Exposed	shaded
7	Time of day	16	17	11	14
8	Elevation change from weather station	above	above	L	L
9	Aspect	South	South	South	South
10	Slope (0-30% or >30%)	>30%	0-30%	0-30%	0-30%
11	Fuel moisture correction%- using Month table	2	5	0	4
12	Initial fine dead fuel moisture (line 3 + line 11)	**10**	**13**	**4**	**12**

[1]Less than 50% shading of surface fuels

Figure 1. Location of the Siahkal forest area and Golestan National Park (GNP) sites in northern Iran.

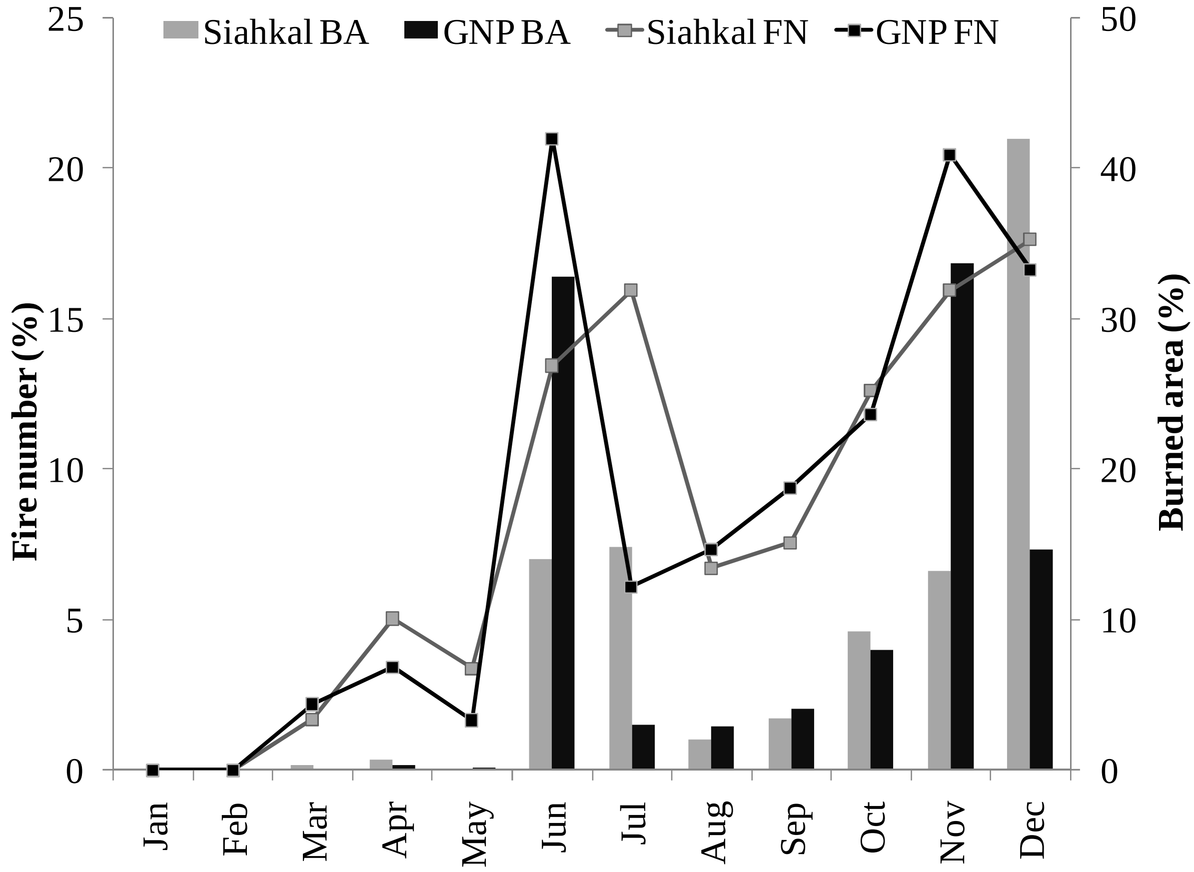

Figure 2. Monthly mean fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000-2011).

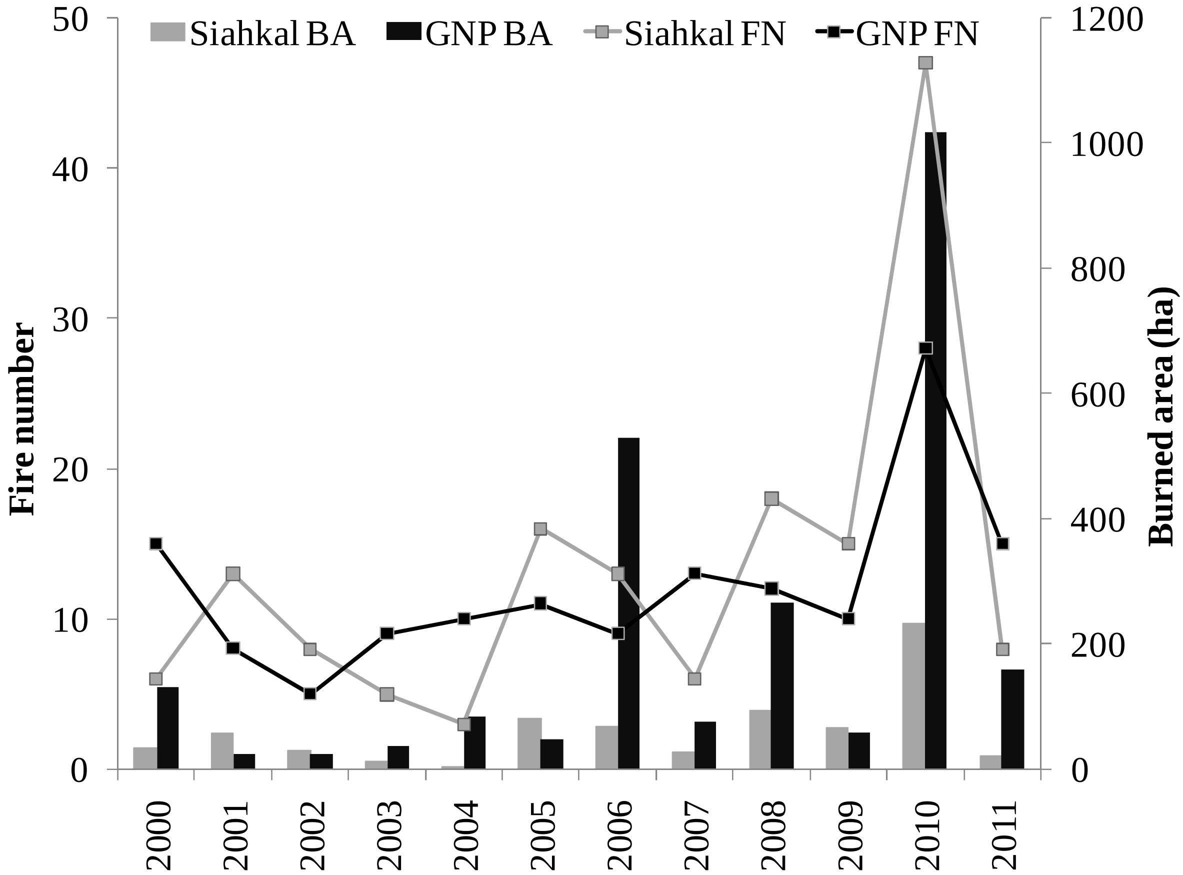

Figure 3. Fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000-2011).

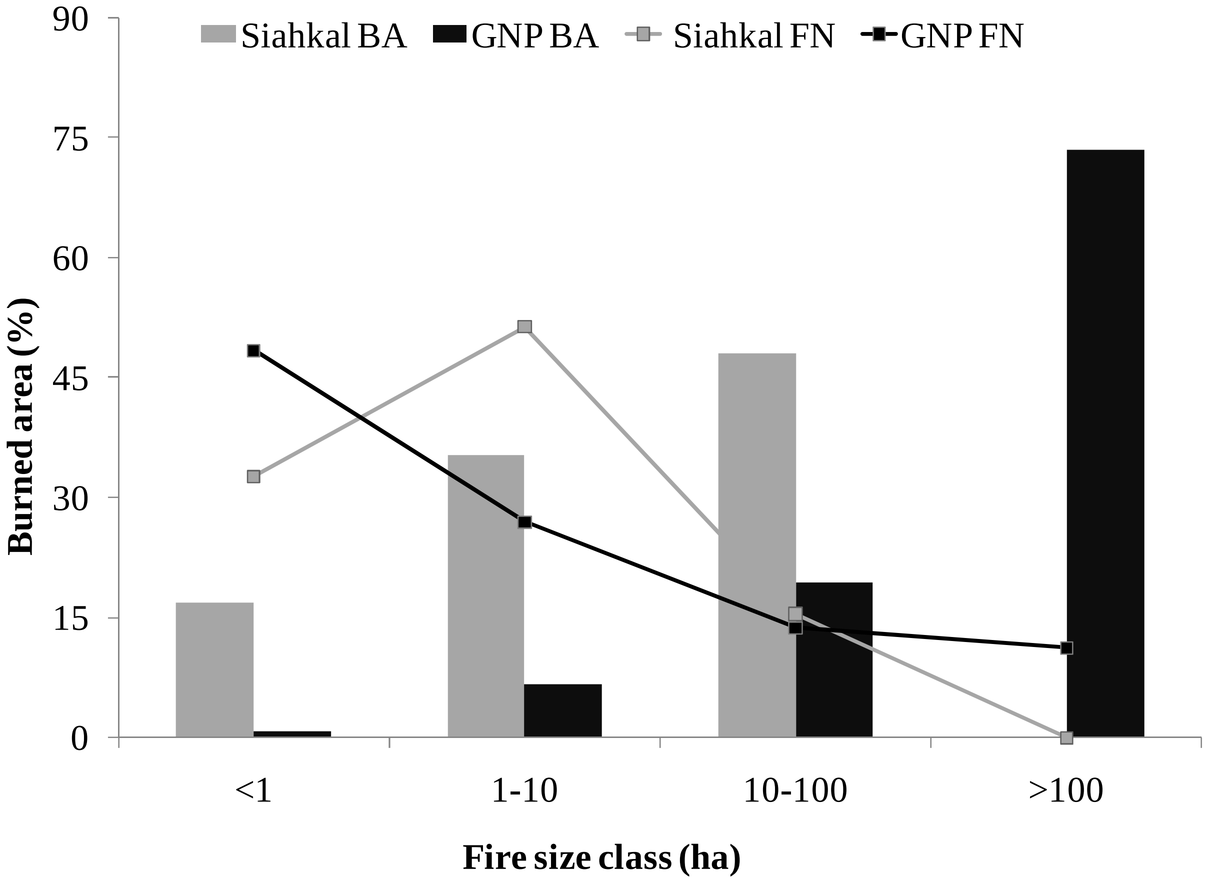

Figure 4. Historical relationship between fire size categories and percentage of fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000-2011).

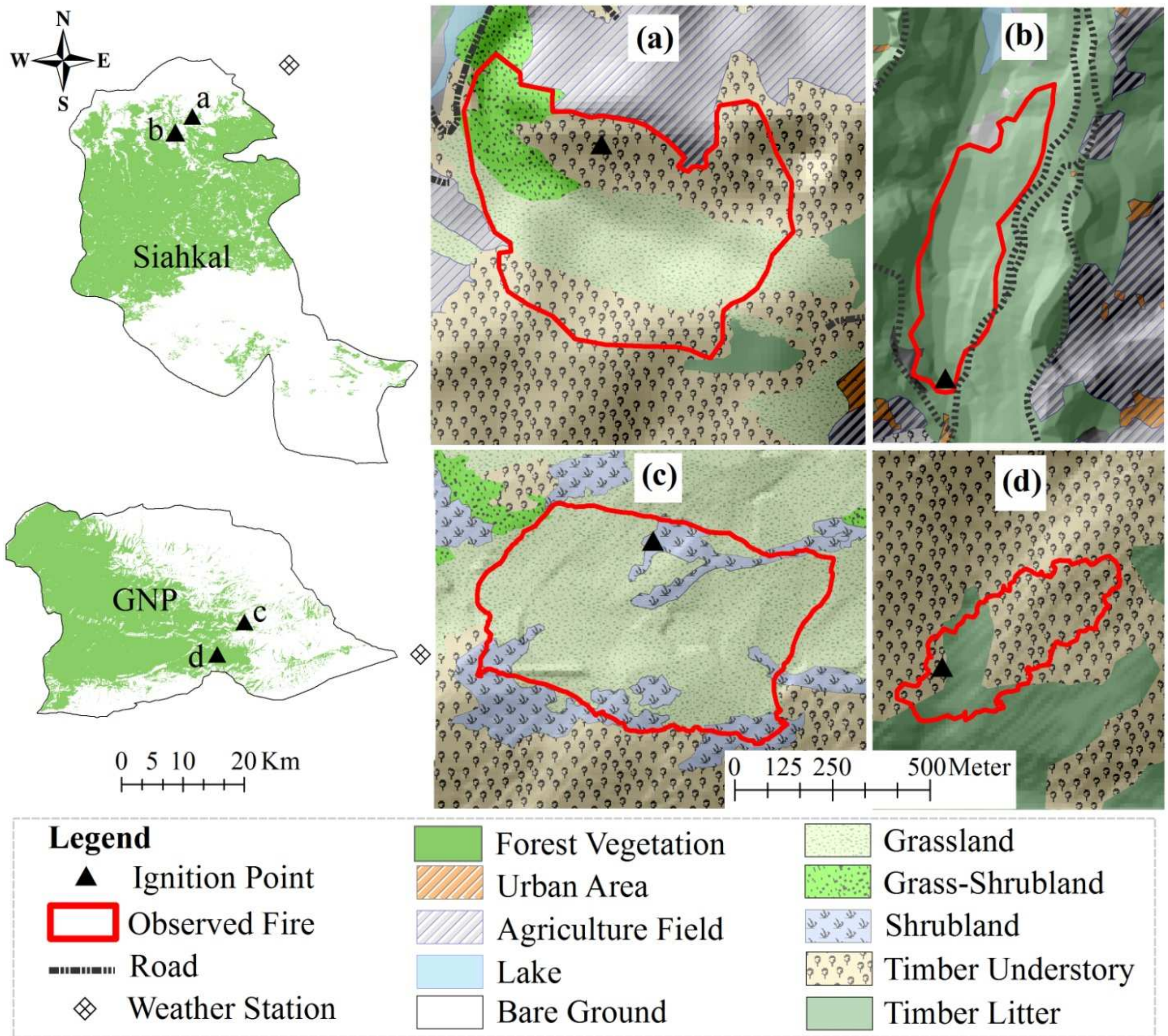

Figure 5. Fuel type maps of the sites where the selected fire events occurred: (a) Toshi and (b) Malekroud in Siahkal forest area; (c) YekeBermagh and (d) Gharangi in GNP. The nearest weather stations to the fire events are presented in the map.

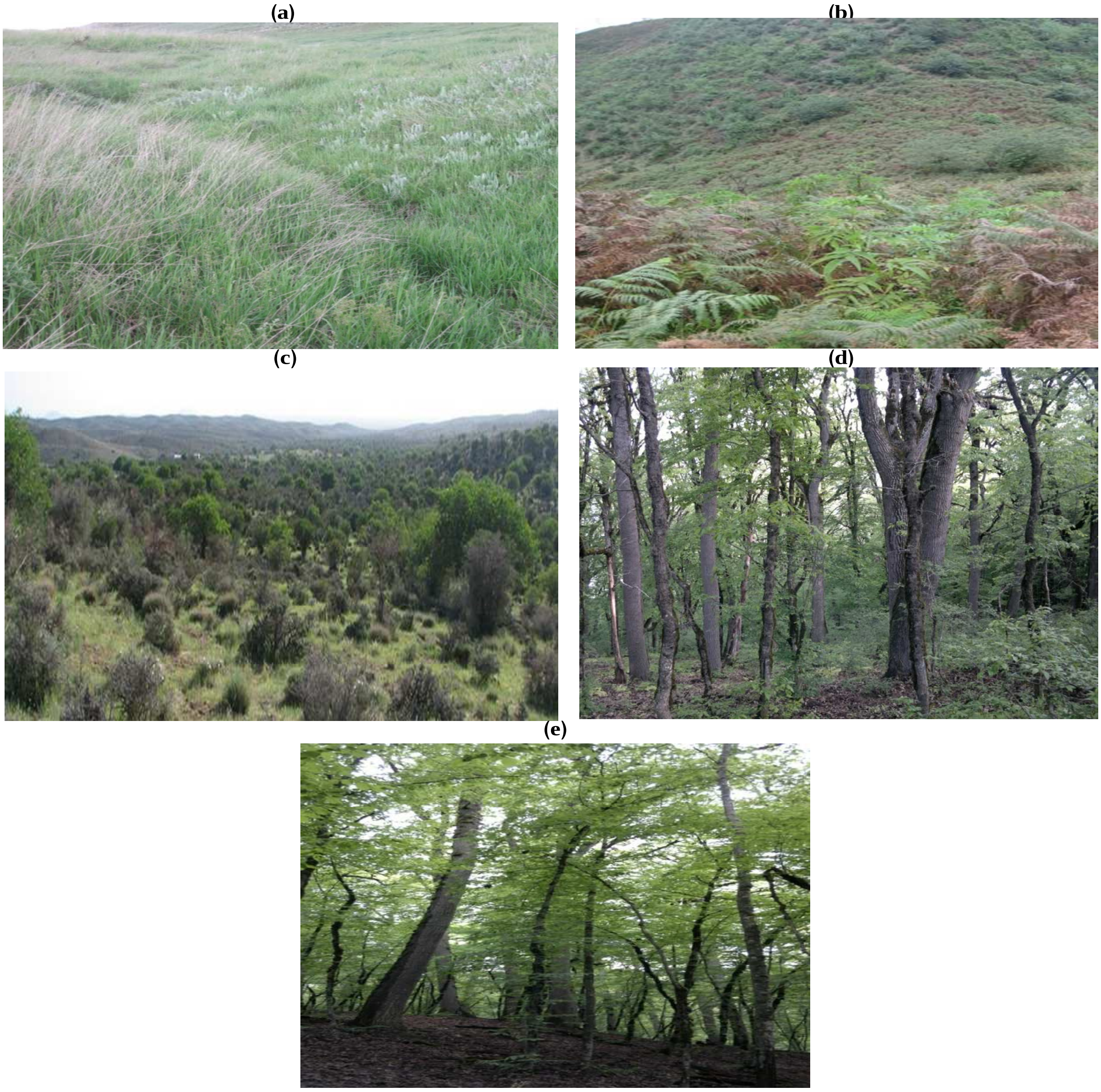

Figure 6. Photo guide of the main fuel types of the study areas: (a) grasslands (GR3, GR4, GR5, GR6, GR7 and FM3 fuel models), (b) grass-shrublands (GS1, GS2, GS3 and GS4 fuel models), (c) shrublands (SH1, SH2, FM5 and FM6 fuel models), (d) natural mixed forest (TU1, TU2, TU3, TU5, FM8, FM9 and FM10 fuel models), and (e) natural pure forest (TL2, TL6, TL8, TL9, FM9 and FM10 fuel models).

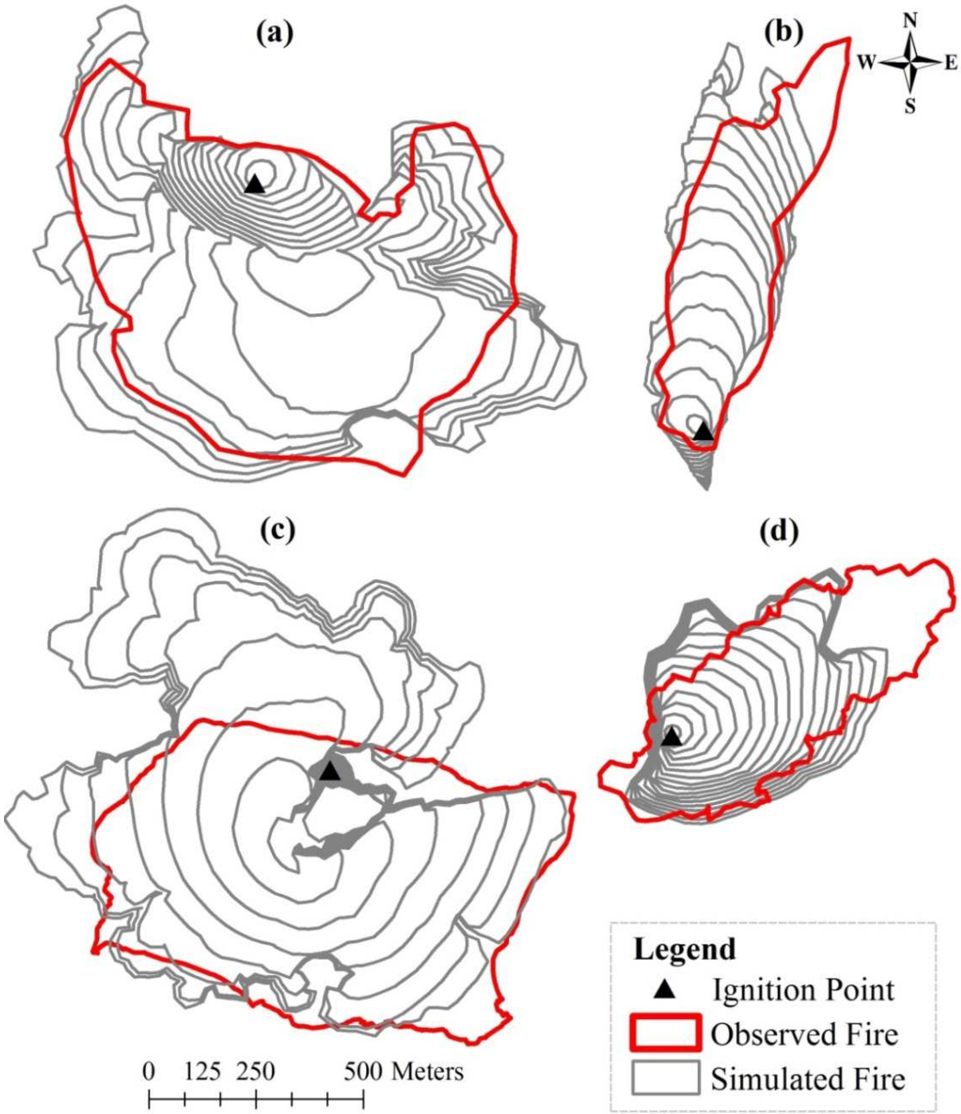

Figure 7. Fire spread perimeters (30 minute interval) of the best FARSITE simulations (grey; III for Toshi, II for Malekroud, VI for YekeBermagh and I for Gharangi; Table 4) vs. observed fire perimeters (red): (a) Toshi, (b) Malekroud, (c) YekeBermagh, (d) Gharangi.

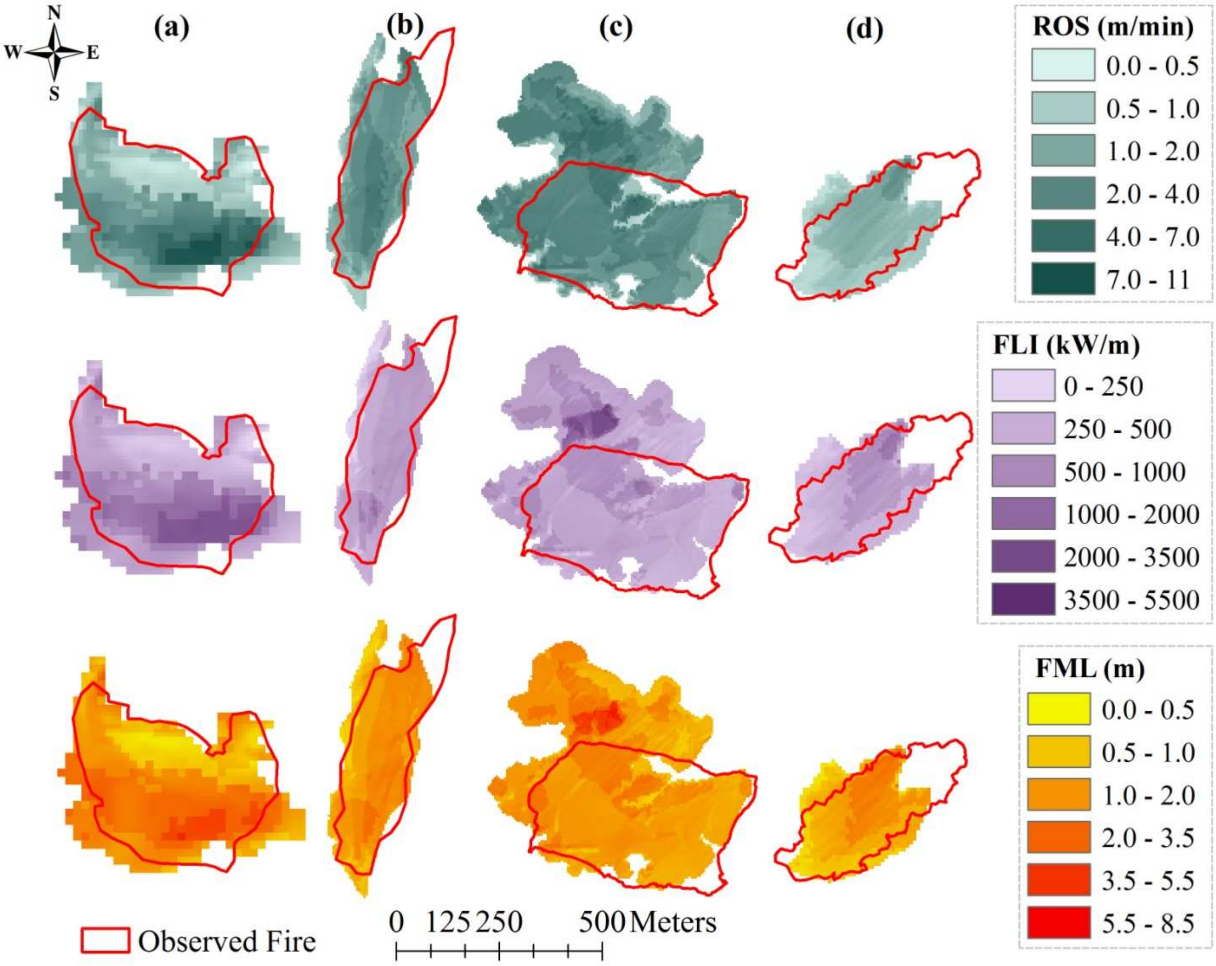

Figure 8. Simulated outputs of rate of spread (ROS), fireline intensity (FLI) and flame length (FML) for the most accurate simulation (III for Toshi, II for Malekroud, VI for YekeBermagh and I for Gharangi; Table 4): (a) Toshi, (b) Malekroud, (c) YekeBermagh, (d) Gharangi (see Table 4).