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Calibration of FARSITE simulator in northern Iranian 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 the FARSITE fire spread model considering a set of recent wildfires that occurred in northern Iranian 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 in 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 around the world (Keeley and Fotheringham, 2001; Pausas et al., 2008; Banj Shafiei et al., 2010; Bracmort, 2012). Every year, about 6000 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 Iranian forests are mostly caused by anthropogenic activities, similar to other areas (Syphard et al., 2007; Bird et al., 2008; Romero-Calcerrada et al., 2008; Martinez et al., 2009), and represent the main threat to protected natural areas. The northern Iranian 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 and badger, and plants, such as the Persian ironwood, Caspian beech, the velvet maple and the Caspian locust.

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 (FMC) (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 and under changing weather and fuel moisture conditions (Finney, 1998; Viegas et al., 1998; Arca et al., 2007, 2009; Forthofer, 2007; Ager et al., 2010, 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 1990s, such 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). FARSITE is a spatially and temporally explicit fire simulation system developed at the Missoula Fire Sciences Laboratory of the USDA Forest Service and is still currently 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 using 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 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 is the primary step to applying the simulator at larger scales (Ager et al., 2007; Stratton, 2006; Salis et al., 2013). 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), 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, canopy characteristics and 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 and height of live and dead biomass that contribute to the size, intensity and duration of a fire (Scott and Burgan, 2005). Several studies developed photo guides and collections of standard (Anderson, 1982; Scott and Burgan, 2005) and local custom fuel models (Dimitrakopoulos, 2002; 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 be used as input for fire spread modeling and in combination with custom fuel models when available (Duguy et al., 2007; Arca et al., 2009; Boboulos et al., 2013). Although spatial data availability increased worldwide in recent years (e.g., 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 and land use land-cover characteristics (Pettinari et al., 2014).

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 (ROS), fireline intensity (FLI) and flame length (FML) – 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 considered a set of four fires that occurred in the southern Caspian forests of northern Iran, specifically in the Siahkal forest area and in Golestan National Park (GNP; Fig. 1). The south Caspian forests (16 481.95 km^2) cover about 1.2 % of the whole of Iran (Marvi Mohadjer, 2005) and range from sea level up to 2500 m a.s.l. (Siadati et al., 2010). The area presents contrasting bioclimatic differences in comparison to 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 1050 km^2 and presents a very high altitudinal range from the lowest areas at 10 to the highest mountains at 2500 m a.s.l. (Fig. 1). The annual precipitation ranges from 600 mm in the southern part to 2000 mm in the northern and highest mountains, and most of the annual rainfall occurs in autumn. Air relative humidity exceeding 80 % is responsible for frequent fogs at the highest altitudes. The average annual temperature is 16 and 25 °C in summer. Average minimum temperatures of the coldest month are usually over 0 °C (Akhani et al., 2010). The Siahkal forest area is lo-

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

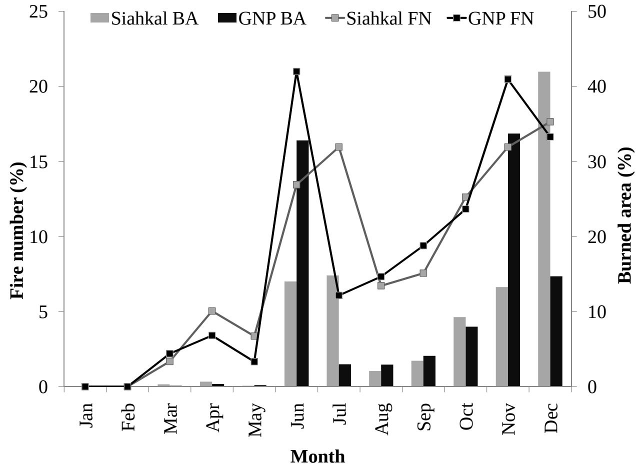

Figure 2. Monthly mean fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000–2011; data from Department of Forestry, Natural Resources Office, Guilan, and Department of Environment, Golestan, Iran, personal communication, 2011, 2012).

cated in the long, narrow vegetation belt on the northward slopes of the Alborz Mountains and constitutes the majority of the Eurosiberian flora in Iran (Djamali et al., 2009). The highest proportion of the Siahkal area is covered by forests (~ 46 %) that are dominated by temperate broad-leaved deciduous trees such as various thermophilous Tertiary relict species (e.g., *Zelkova carpinifolia*, *Parrotia persica*, *Pterocarya fraxinifolia*, *Quercus castaneifolia*) and Asian subtropical trees in some cases (e.g., *Diospyros lotus*, *Gleditsia caspica*, *Danae racemosa*, *Albizia julibrissin*) (Table 1; Akhani, 1998; Akhani and Ziegler, 2002; Leestmans, 2005; Leroy and Arpe, 2007).

The Golestan National Park is situated in northeast Iran and covers about 920 km^2 of land (Fig. 1). The National Park is located in a transitional position between the sub-humid south Caspian region and the semi-arid zones of the central and east-central Iranian Plateau. The GNP ranges from 450 to 2400 m a.s.l. 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 to more than 1000 mm in some central parts of the GNP (Akhani, 1998). The mean annual temperature is 11.5–17.5 °C and the mean summer temperature is 28 °C (Akhani, 1998). 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 ~ 2000 ha. 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 people (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 that rarely exceed 0.3 m flame height (Adel et al., 2012).

Wildfires in the GNP, as well as in the Siahkal forests, are distributed from June to December, with two peaks in the number of fires and area burned in June–July and November–December (Fig. 2). Although observed annual fires and burned area in the GNP and the Siahkal forests present high interannual variability during the period 2000–2011, the hardest wildfire campaigns correspond to the latest years and especially to 2010 (Fig. 3). During the period 2000–2011, the Siahkal area experienced on average about ~ 13 fires per year and about ~ 60 ha burned (Department of Forestry, Natural Resources Office, Guilan, Iran; Fig. 3). Approximately 85 % of the fires in Siahkal burned less than 10 ha; a small number of fires (about 15 %) is responsible for half of the area burned (Fig. 4) and no fires larger than 100 ha were observed in the studied period. In the GNP during the period 2000–2011, ~ 12 fires per year have been recorded on average, with ~ 200 ha burned (Fig. 2). In this area, the largest fires (> 100 ha) accounted for about 15 % of the fires and were responsible for almost 75 % of the total area burned

Table 1. Case study description.

Site	Siahkal		Golestan National Park	
Wildfire	Toshi	Malekroud	YekeBermagh	Gharangi
Latitude of the ignition point	37°11′	37°03′	37°22′	37°21′
Longitude of the ignition point	49°88′	49°84′	56°03′	56°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 communis* L., *Buxus hyrcana* 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 in LT)	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

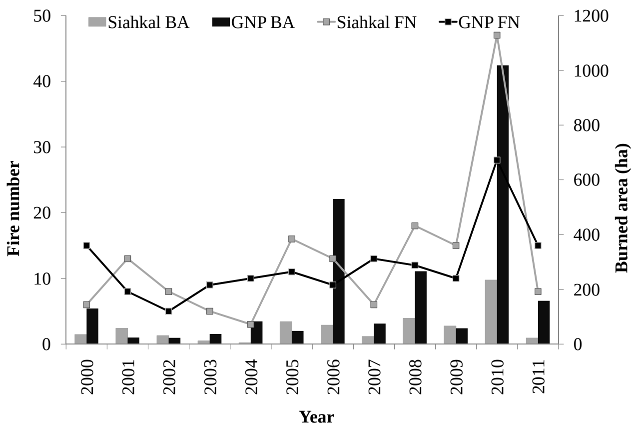

Figure 3. Fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000–2011; data from Department of Forestry, Natural Resources Office, Guilan, and Department of Environment, Golestan, Iran, personal communication, 2011, 2012).

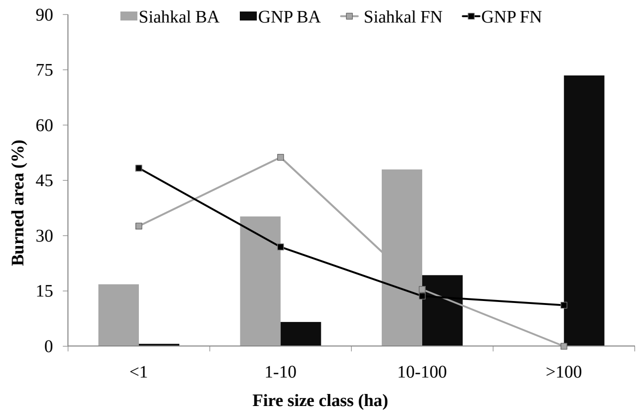

Figure 4. Historical relationship between fire size categories and percentage of fire number (FN) and burned area (BA) in Siahkal forest area and GNP (2000–2011; data from Department of Forestry, Natural Resources Office, Guilan, and Department of Environment, Golestan, Iran, personal communication, 2011, 2012).

(Department of Environment, Golestan, Iran; Fig. 4). The largest wildfire in the GNP (Cheshme-Sardar fire event) was observed on 15 November 2010 and burned 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 (Fig. 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 location coordinates were determined from fire reports (Department of Forestry, Natural Resources Office, Guilan, and Department of Environment, Golestan, Iran, personal communication, 2011, 2012) and interviews with forest rangers, firefighters and park managers, and burned area perimeters were recorded after the fire events using the Global Positioning System (GPS).

The Toshi wildfire occurred near the village of Toshi (lat 37°11′ N, long 49°88′ E) in August 2010, and the 25 h fire event burned 34 ha (Fig. 5; Table 1) of 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 (Fig. 5). The weather was characterized by a maximum temperature of 35 °C, average relative humidity of 50 % and northeast winds (Table 2). The fire spread towards southeast, driven by the wind and the topographic conditions.

The Malekroud wildfire occurred near the town of Malekroud (lat 37°03′ N, long 49°84′ E) in December 2010 and burned approximately 24 ha covered by heterogeneous structural characteristic mature forest in a low-elevation area (Fig. 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 h near a road along the northern border of the fire perimeter (Fig. 5). The day was characterized by a moderate maximum temperature (∼ 25 °C), average relative humidity of 58 % and southern winds. The fire was driven northward by the mild slope and the wind.

The YekeBermagh wildfire occurred in the southern part of the Golestan National Park (lat 37°22′ N, long 56°03′ E) in July 2011 (Fig. 5; Table 1). The northern part of the YekeBermagh 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 was 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 in March 2011, in the southern part of the Golestan National Park (lat 37°21′ N, long 56°02′ E), and burned about 10 ha (Fig. 5; Table 1) of dense-mixed woodland. The area presents a mountainous orography with an altitude range between 1200 and 2160 m a.s.l. The fire weather was mild, with a maximum air temperature of 17 °C and average relative humidity of 49 %. The fire spread towards the north and northeast, driven by southwest 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 on the 1 : 25 000 land-cover maps of 2004

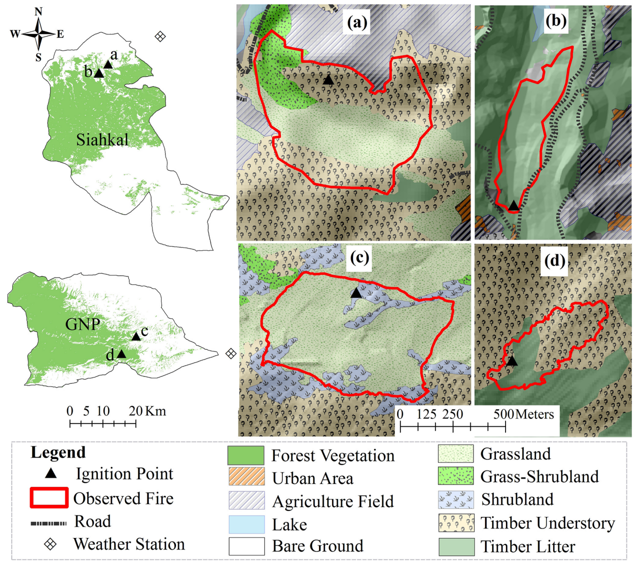

Figure 5. Fuel type maps of the sites where the selected fire events occurred: **(a)** Toshi and **(b)** Malekroud in Siahkal forest area; **(c)** YekeBermagh and **(d)** Gharangi in GNP. The nearest weather stations to the fire events are presented on the map.

(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 standard fuel model assignment. Furthermore, with the georeferenced 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-intercept sampling (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 georeference 188 and 250 sampling plots, respectively (Table 3). Considering the spatial distribution and the coverage degree for the different species within the different vegetation types, 1 m × 1 m square sampling plots were used for herbaceous fuel types and 10 m × 10 m square sampling plots for shrubby and forested vegetation types. We measured species composition, fuel-bed depth, litter type (conifer or broadleaf), herbaceous cover, shrub cover and canopy cover (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. We also produced a photo guide for main fuel models types (Fig. 6)

In this study, standard fuel models (Anderson, 1982; Scott and Burgan 2005) were assigned to the existing vegetation

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

Site	Siahkal[1]		Golestan National Park[2]	
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

[1] Lahijan Station (−2 m a.s.l.; lat 37°11′, long 50°00′), located 15 km away from the northeast boundary of the Siahkal forest area. [2] Robate-GharehBil automatic weather station (1282 m a.s.l.; lat 37°21′, long 56°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.

			Surface fuel model data					Assigned fuel models		FMC[1] (%) Dead fuel (%)			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 h[2]	10 h[3]	100 h[4]	LH[5]	LW[6]
Toshi	grassland	55	65.5	–	75	–	30	GR3, GR5, GR6	FM3	11	12	14	0	0
	grass–shrubland	27	82.0	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	5.0	conifer and broadleaf	15	10	75	TL2, TL6, TL8, TL9	FM9, FM10	14	15	17	50	100
YekeBermagh	grassland	130	45.0	–	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	4.0	broadleaf	15	5	75	TL2, TL6, TL9	FM9, FM10	13	14	16	75	100

[1] Fuel moisture content; [2] 0–0.6 cm diameter particle size class; [3] 0.6–2.5 cm diameter particle size class; [4] 2.5–7.6 cm diameter particle size class; [5] live herbaceous; [6] live woody.

and land use land-cover types based on their similarities in structural characteristics (Figs. 5, 6; Table 3). 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 fuel models were assigned to the timber litter, hardwood litter and litter and understory areas. Non-burnable (NB) fuel models were assigned for roads, buildings, urban areas, ploughed agricultural lands, water bodies and bare ground; in that case the geospatial information was gathered from the 1 : 25 000 digital topographic maps (National Cartographic Center of Iran).

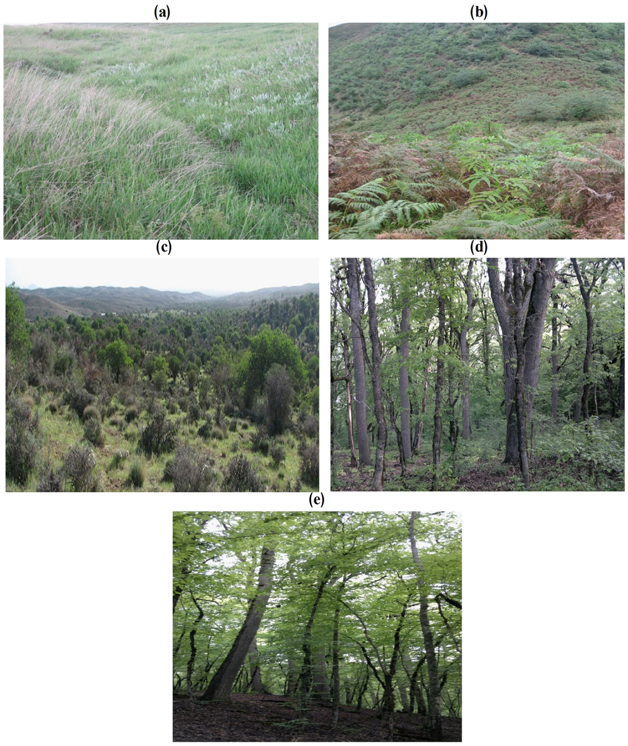

Figure 6. Photo guide of the main fuel types of the study areas: **(a)** grasslands (GR3, GR4, GR5, GR6, GR7 and FM3 fuel models), **(b)** grass–shrublands (GS1, GS2, GS3 and GS4 fuel models), **(c)** shrublands (SH1, SH2, FM5 and FM6 fuel models), **(d)** natural mixed forest (TU1, TU2, TU3, TU5, FM8,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

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 (i.e., 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 with 10 m resolution. Topography layers were derived from the digital elevation model (10 m resolution; National Cartographic Center of Iran, NCC) for each study area. As previously described, surface fuel 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 wind direction, were collected from the weather stations nearest to the wildfire case studies (Fig. 5 and Table 2).

Initial fuel moisture content for the 1, 10 and 100 h dead fuels (Table 3) was determined following the methodology proposed by Rothermel (1983; Table A1). With this method, we estimated the fine dead FMC for each case study, and then we derived 10 and 100 h dead moisture by adding 2 and 4 %, respectively, to the 1 h 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 (i.e., 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 due 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 ($\mathrm{m\,min^{-1}}$), fireline intensity ($\mathrm{kW\,m^{-1}}$) and flame length (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). Sørensen'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).

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

$$\mathrm{SC} = \frac{2a}{2a+b+c}, \tag{1}$$

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

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

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

Table 4. Statistical evaluation of FARSITE performances for different combinations of standard fuel models.

Case study (observed fire size in ha)	Simulation number	Fuel model code	SC[1]	K[2]	a[3] (ha)	b[4] (ha)	c[5] (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

[1] Sørensen's coefficient value; [2] Cohen's kappa coefficient value; [3] burned area agreement between observed and modeled fire; [4] simulation overestimation; [5] simulation underestimation.

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 0 and 1, with values close to 1 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 (Fig. 7, 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 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 simulation III (Fig. 7a, Table 4), where about 30.1 ha of the final fire area coincided with the observed fire size, while 4.1 and 5.5 ha were underestimated and overestimated, respectively, by FARSITE. As previously pointed out, the best values of SC and K coefficients were obtained in simulation III ($SC = 0.86$, $K = 0.82$; Table 4), whereas the other sim-

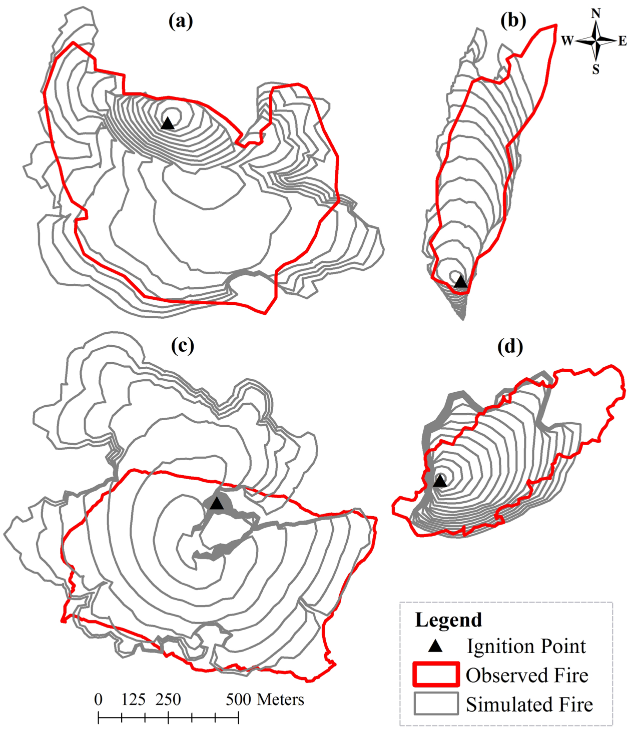

Figure 7. Fire spread perimeters (30 m interval) of the best FARSITE simulations (grey; III for Toshi, II for Malekroud, VI for YekeBermagh and I for Gharangi; Table 4) vs. observed fire perimeters (red): **(a)** Toshi, **(b)** Malekroud, **(c)** YekeBermagh, **(d)** Gharangi.

ulations 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).

Simulation II of the Malekroud wildfire event (Fig. 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 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 simulation VI of the YekeBermagh case study (Fig. 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 ha of the fire area was underestimated (Table 4). The statistical test showed that in 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 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 simulation I of the Gharangi wildfire event (Fig. 7d, Table 4), about 7.5 ha of the observed fire area was correctly simulated as burned area by FARSITE. The extent of the underestimation by the simulation was approximately 2.6 ha and the overestimation was 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 with the best simulations of FARSITE for each case study, the higher SC and K values were obtained using the GR6 grassland model in simulation III of the Toshi fire (SC = 0.92; K = 0.87; Table 5) and the TL9 timber model in simulation I of the Gharangi fire (SC = 0.91, K = 0.91; Table 5). The worst performances were provided by the model TU1 in simulation I of the 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, fireline intensity and flame length were analyzed for each of the fuel models used in the four case studies (Fig. 8 and Table 5). The fire simulation outputs showed complex patterns that were generally related to the dominant fuel types and the topography.

Overall, the average wind speed conditions ranged between 14 and 23 km h^{-1} for the case studies presented (Table 2), and this is one of the main reasons why fires did not show high, fast-spreading output values (0.53–2.61 m min^{-1} average ROS; Table 5). 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 to 10.84 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) was obtained for the areas covered by mixed hardwood forest (TU1) and pure hardwood forest (TL6) in the 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).

Table 5. Statistical evaluation of the best FARSITE simulation (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.

Case study (best simulation)	Fuel Model	SC[1]	K[2]	a[3] (ha)	b[4] (ha)	c[5] (ha)	Observed fire size (ha)	Simulated fire size (ha)	ROS[6] (m min^{-1})	FLI[7] (kW m^{-1})	FML[8] (m)
Toshi (III)	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
	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
	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
	TU3	0.75	0.73	6.93	2.90	1.80	8.73	9.83	1.61 ± 1.55	239.38 ± 216.60	0.88 ± 0.42
	Average	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
	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
	Average	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)	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
	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
	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
	Average	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)	TU1	0.47	0.45	0.90	0.82	2.18	3.08	1.72	0.32 ± 0.29	85.55 ± 78.41	0.45 ± 0.36
	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
	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
	TL9	0.91	0.91	2.11	0.40	0.00	2.11	2.51	0.63 ± 0.19	149.43 ± 83.11	0.74 ± 0.20
	Average	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

[1] Sørensen's coefficient value; [2] Cohen's kappa coefficient value; [3] burned area agreement; [4] FARSITE overestimation; [5] FARSITE underestimation; [6] rate of spread; [7] fireline intensity; [8] flame length.

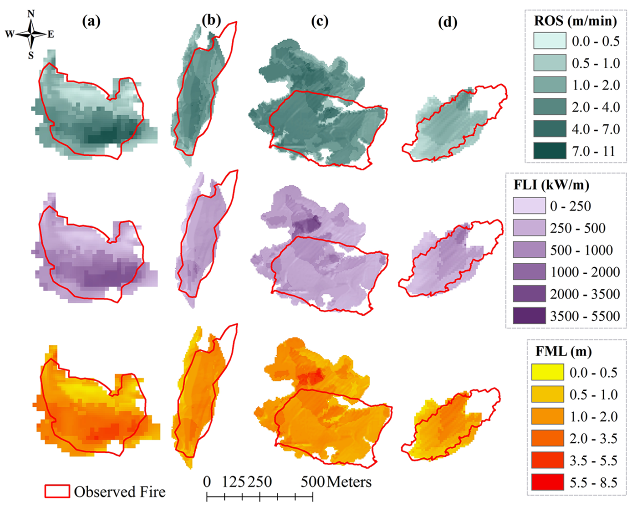

Figure 8. Simulated outputs of rate of spread (ROS), fireline intensity (FLI) and flame length (FML) for the most accurate simulation (III for Toshi, II for Malekroud, VI for YekeBermagh and I for Gharangi; Table 4): **(a)** Toshi, **(b)** Malekroud, **(c)** YekeBermagh, **(d)** Gharangi (see Table 4).

In addition to the ROS, relevant differences in terms of fire intensity (i.e., FLI and FML) were found between the different vegetation types. The high-fuel-load tall grass (GR6) presented the highest values (average FLI > 350 kW m^{-1} and FML > 1.4 m; Table 5) and the compact litter and understory (TU1, TU2 and TL6) showed the lowest values (average FLI < 100 kW m^{-1} and FML < 0.5 m; Table 5). Nonetheless, high values were also locally associated with shrubby fuel models (SH1 and SH2; FLI < 250 kW m^{-1} and FML > 1 m; Table 5) in YekeBermagh wildfire case study. The obtained fire intensity results in the different fuel models resembled observed flame lengths during the analyzed fire events.

4 Discussion

The wildfire spread depends on complex interactions 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 in the understanding of potential fire behavior, improve logistics and decision-making and thereby improve awareness and safety of firefighters. Nevertheless, adoption and application of fire spread modeling in a given landscape should be preceded by a sound calibration process, as well as by 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 accurately 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). Additionally, calibration and validation of fire simulations in general are also made difficult by the multiple sources of error in data, which are confounded by the error of the model itself. These sources may include insufficient accuracy in spatial fuels information, the distance between the weather station locations to the area where the fire occurred, the mapping of fire perimeters or eventual errors from the user who runs the models (e.g., model parameter settings) (Finney et al., 2011). Many studies have shown that the use of both wind field data and appropriate custom fuel models is essential to obtain reasonable simulations of fire spread and behavior (Arca et al., 2007; Salis, 2008; Forthofer, 2007). In the current study, although the simulations with FARSITE were run at fine scale (10 m) using the most accurate available geospatial information for the study areas, the fire spread spatial output data accuracy might have been influenced since the fuels and topography input maps derived from 1 : 25 000 scale land use land-cover and digital elevation models.

As highlighted by 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 was also applied at landscape scale for several fire modeling and fire likelihood analysis (Bar Massada et al., 2011), other simulators like FlamMap and its command line Randig (also based on Rothermel's fire spread model; Finney et al., 2006) present some advantages with respect to FARSITE when working at large scales (thousands of hectares and square kilometers) and with a huge number of fire ignitions (several thousands for fire modeling) (Ager et al., 2007, 2010).

The goal of this paper was to assess the capabilities of FARSITE in replicating wildfire spread and behavior in northern Iran, where 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, 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., 2006, 2007, 2009; Fernandes et al., 2006; Salis et al., 2010, 2013, 2014b). Although 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 when 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 (1982) fuel models 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 in a number of fuel models showed average values under suppression capabilities for fire extinction crews and equipment (Andrews et al., 2011; Table 5). 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 with high-fuel-load tall grass and shrubby fuel models. 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). The heading fire burning areas dominated by tall grass (GR6 and GR7) exhibited the highest rate of spread ($ROS > 5\,m\,min^{-1}$; Table 5) with moderate flame lengths ($FML < 2.5\,m$; Table 5), and such fire behavior presented the most important fire suppression difficulties due to a high rate of spread rather than the fireline intensity. The limitations in effectively controlling fire spread were locally amplified in certain areas where the terrain steepness was aligned with wind direction (e.g., Toshi wildfire, Fig. 8). On the other hand, fire extinction did not present relevant complications in crown fire activity lacking timber litter and timber understory fuel model areas, where the fuel moisture content, higher than in open areas, did not support a hazardous fire behavior.

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 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 scale land use land-cover maps. The best match between observed and simulated area burned was observed on grasslands fuel types.

Overall, 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 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 further investigation and work of field sampling and mapping is needed. Furthermore, this work provides a useful methodology that can be replicated in the southern Caspian forests to characterize fire likelihood and intensity and increase local awareness of the risks posed by fires spreading in such forest ecosystems.

Nevertheless, there were some limitations in the present study (i.e., the insufficiency or lack of custom fuel models, high-resolution wind field data, the lack of accurate information on observed fire spread and medium-scale feature-derived landscape input maps) that may have affected the accuracy of the results. Further efforts in future studies should be carried out to simulate locally the spatial variation of wind speed and direction, improve the standard fuel model assignments to the different vegetation types and develop a more precise fuel model guide for northern Iran with custom models through field samplings on local vegetation complexes.

Appendix A

Table A1. Data used for calculating initial dead fuel moisture content (FMC) for the wildfire case studies. The FMC values were calculated according to the method proposed by Rothermel (1983).

	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* 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

* Less than 50 % shading of surface fuels.

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