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Evaluating fire modelling systems in recent wildfires of the Golestan National Park, Iran

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This study analyzed differences between actual and modelled fire predictions for two recent fires that affected the Golestan National Park in northeastern Iran. FARSITE and FlamMap minimum travel time (MTT) fire modelling systems were used to compare spatial differences in burned area between observed and modelled fires. Then, the spatial variability in fire spread and behaviour related to differences in fuel types and topography was analyzed. Comparison between the observed and simulated fire perimeters showed a relatively good agreement. For both case studies, the simulations performed with the MTT algorithm presented slightly higher accuracy than the FARSITE ones. Although we found spatial differences in fire intensity and rate of spread modelling outputs, the average values in burned areas provided by FARSITE and FlamMap MTT simulations were very similar. The comparison of fire spread models provided a better understanding of their potential limits and differences in fire growth and behaviour predictions over heterogeneous-fuel landscapes, complex topography and changing weather conditions.

Introduction

In the last decades, an increasing number of wildfires have threatened and caused substantial losses in forests and other natural resources of northern Iran (Poorshakoori Allahdeh *et al.*, 2011; Eskandari *et al.*, 2013; Jahdi *et al.*, 2014;2015). After the devastating fire seasons that affected Mediterranean Europe (e.g. Portugal, 2003, 2005; Italy and Greece, 2007, 2009) and other countries (e.g. USA, 2000; Canada, 2003, 2004; Australia, 2006, 2007), the demand for models and tools for supporting wildfire spread monitoring and prediction has risen in recent years (Ager *et al.*, 2011; Salis *et al.*, 2014; Schmuck *et al.*, 2014). Fire modelling provides an analytical framework to characterize and predict fire spread and behaviour in diverse and complex fire environments (Van Wagtendonk, 1996; Stephens, 1998), and can be useful in wildfire management, landscape planning, risk assessment and risk mitigation (Loureiro *et al.*, 2006; Ager *et al.*, 2007; Calkin *et al.*, 2011; Salis *et al.*, 2013;2014;2015; Alcasena *et al.*, 2015). Many fire modelling systems such as FARSITE (Finney, 1998), NEXUS (Scott, 1999), SPREAD (Mendes-Lopes and Aguas, 2000), FlamMap (Finney, 2006a), FSIM (Finney *et al.*, 2011), BehavePlus (Andrews, 2007), ForeFire (Balbi *et al.*, 2009) and Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE; Rebain, 2010), and many others (Peterson *et al.*, 2009; Ghisu *et al.*, 2014) have been developed in the recent years. The fire modelling systems involve explicit spatio-temporal modelling of forest fire spread over large landscapes, often heterogeneous in terms of vegetation and topography, with changing weather conditions and variable fire duration even up to days (Keane *et al.*, 2004; Cui and Perera, 2008), at different resolutions and variable fire front time-step projections (Yang *et al.*, 2008). Thus, it is not only difficult to develop and calibrate these models with the aim of accurately predict fires, but also to validate them under different burning conditions (Trunfio, 2004). Comprehensive data on historical fire occurrence, spread and behaviour, as well as on local-scale environmental conditions in the areas nearby the fire events which are commonly available in North America or Europe, are not usually available in other countries, such as Iran. Therefore, the application of fire modelling systems can be affected by the relatively limited amount of information on fuel types and characteristics, fire weather, topography and fire history. Testing and evaluating fire spread models is an important and fundamental component for both scientific and operational purposes (Albini and Stocks, 1986). Overall, the accuracy of the fire modelling systems depends on three major factors (WenBin and Perera, 2008): (1) the availability and quality of input data, (2) the theoretical basis of the fire behaviour model and (3) the fire growth algorithm.

Much of wildland fire planning and decision-making is intrinsically spatial and requires calculation, display, and analysis of potential fire spread and behaviour across large landscapes (Finney, 2003). Two widely used simulators have been developed in recent years in order to facilitate such tasks: FARSITE (Finney, 1998) and FlamMap (Finney, 2006a). FARSITE is a single fire event spatio-temporal fire spread and behaviour modelling system, which considers heterogeneous terrain, different fuel models and changing weather (e.g. wind speed and wind direction) and fuel moisture content conditions. The spatial growth of fire perimeters in FARSITE is modelled using the Huygens' principle, in which the fire perimeter is obtained merging the vertex positions of elliptical shape spread vectors at a given time-step, and primarily depends on the wind-slope vector (Alexander, 1985; Richards, 1995). FARSITE produces many types of fire behaviour's outputs such as fire spread polygons (isochrones), time of arrival (h), flame length (m), fireline intensity (kW m^{-1}), rate of spread (m min^{-1}) and crown fire activity (class). On the other hand, FlamMap computes potential fire behavior characteristics at an arbitrary resolution set by the user for a single set of environmental conditions (constant weather and fuel moisture content scenario for the extreme fire analysis) giving the possibility to saturate the landscape with thousand independent fires. FlamMap incorporates the minimum travel time (MTT) algorithm, which computes the fastest straight-line fire growth between cell corners and produces a minimal distortion to fire shapes because there are no limits on angles or distances for searching (Finney, 2002). The MTT algorithm replicates fire growth by the Huygens' Principle, where the fire edge growth (and behaviour) is a vector or wave front (Richards, 1990; Finney, 2002). FlamMap can be run from project level up to large landscape scales in three calculation modalities: (1) individual pixel basic fire behaviour to generate outputs such as fire intensity (kW m^{-1}), rate of spread (m min^{-1}), flame length (m) and crown fire activity (class); (2) minimum MTT-based fire spread from individual fire or ignition line to generate outputs such as rate of spread (m min^{-1}), fire intensity (kW m^{-1}) and preferential flow-paths (straight-line transects); and (3) MTT-based fire spread from multiple ignition sources to generate burn probabilities, conditional flame lengths (m) and fire sizes (ac). FlamMap outputs are mostly used for landscape scale fire behaviour analysis (e.g. pre- and post-treatment effectiveness) and to identifying hazardous fuel and topographic combinations, thus aiding wildfire managers in prioritization and assessment (Stratton, 2004).

There are several studies that used FARSITE and FlamMap in US, southern Europe and elsewhere for fire spread and behaviour modelling with different purposes. FARSITE has been used for many applications, such as observed fire replication on heterogeneous conditions (Sanders, 2001; Duguy *et al.*, 2006; Arca *et al.*, 2007; Salis, 2008; Jahdi *et al.*, 2015), ignition location effect comparison on burn patterns (Bar Massada *et al.*, 2011), wildfire exposure analysis (Bar Massada *et al.*, 2009) and fuel treatment effect evaluation on fire spread (Ryu *et al.*, 2007; Duguy *et al.*, 2007; Schmidt *et al.*, 2008; Stratton, 2008; Cochrane *et al.*, 2012; Wu *et al.*, 2013). The second fire modelling system, FlamMap, has been used in several research studies for quantitative wildfire risk and exposure assessment (Ager et al., 2007;2010;2012; Bar Massada *et al.*, 2009; Thompson et al., 2011, 2013a, b;2015; Parks et al., 2012; Haas et al., 2013; Salis et al., 2013;2014;2015; Kalabokidis et al., 2014a; Mitsopoulos et al., 2015; Alcasena et al., 2015), fuel treatment evaluation (Stratton, 2004; Finney, 2006b;2007; Chung *et al.*, 2013;Thompson *et al.*, 2013c) and analysis of climate change effects on wildfires (Arca *et al.*, 2010; Kalabokidis *et al.*, 2014b).

This study aims to assess the modelled burned area accuracy and the differences in fire spread and behaviour simulation predictions among FARSITE and FlamMap MTT, through the simulation of two recent wildfires that affected the forests of the Golestan National Park in northeast Iran. The results and the methodology can be used for addressing fire management and planning needs, and identifying areas where the fire simulators disagree in predicting fire spread and behaviour. The results are also a useful calibration data set for the model developers.

Methods

Case studies

Two recent fire events that occurred in the southern part of the Golestan National Park (GNP) were chosen for the current study. Golestan National Park is one of the oldest and most ecologically diverse protected areas of Iran, covering ∼920 km^2 of the eastern Iranian Caspian forests (Figure 1). The region is characterized by a variable and rough topography, since the altitude ranges from the 450 m in the southeastern Central plateau, to nearly the 2400 m in the northwestern area on the Alborz Mountains. The weather is characterized by warm summers and cold winters, with an annual average temperature of 11.5–17.5°C and average relative humidity of 60–83 per cent. The precipitation varies from 150 mm $year^{-1}$ in the southeastern to >1000 mm $year^{-1}$ in some central parts of the Park (Akhani, 1998). It is a biodiversity hotspot and one of the most important wildlife sanctuaries of Iran with over 150 species of mountain birds, brown bears, wild cats, tigers, mountain goats, coyotes and foxes (Leylian *et al.*, 2010). The western parts of the Golestan National Park are covered by the Hyrcanian forests (∼40 per cent;, i.e. *Parrotia persica* C.A.Mey., *Quercus castanei folia* C.A.Mey., *Carpinus betulus* L. species) while the eastern, northeastern and southeastern parts are dominated by Irano-Turanian grasslands (∼30 per cent;, i.e. *Festuca drymeia* Mert. & Koch., and *Artemisia sieberi* Besser. species), and Juniperus shrublands (∼5per cent;, i.e. *Juniperus excelsa* M. Bieb. and *Juniperus communis* L. species).

Wildfires in the GNP are distributed from March to December, with the bulk of fire ignition number and area burned between June and November (Department of Environment, Iran, personal communication, 2011, 2012). Fires increased in frequency and severity in the past two decades, with >11 fires $year^{-1}$ that burn 215 ha on average (0.23 per cent $year^{-1}$ of the Goldestan NP) of forest and other lands (1990 to 2010; Department of Environment, Iran, personal communication, 2011, 2012). Small (<10 ha), medium (10–100 ha) and large fires (>100 ha) account, respectively, for the 75, 14 and 11 per cent in terms of fire number, and the 7, 20 and 73 per cent of the burned area. The Cheshme-Sardar fire event in the southern part of the park, which burned ∼850 ha in 5 days during the 2010 autumn catastrophic forest fires, is the largest recorded fire within the GNP. Although some evidences indicate that some ignitions are caused by lightning, anthropogenic activities (largely concentrated in the southern part of the Park) are responsible of most fires (Sarkargar Ardakani, 2007; Zarekar *et al.*, 2013; Mirdeylami *et al.*, 2014; Iranian Forest Brigades, personal communication).

From the available fire database records of the GNP we choose the Yeke-Bermagh and Gharangi fires, since these events were the largest fires for which all the required information for fire modelling (i.e. ignition location, burned area perimeter and wildfire event weather data) were available. For both case studies, ignition locations coordinates were determined from fire firefighters' reports (personal communication, 2011, 2012), and burned area perimeters were recorded after the fire events by Park managers, using a Global Positioning System. The two fires were close to each other and were the most important events during 2011, when several simultaneous fires in the GNP overwhelmed fire suppression capabilities. The Gharangi fire was a ∼14 km h^{-1} southwestern wind driven short fire event that occurred on 28 March 2011, which burned 10 ha in 7 h. The

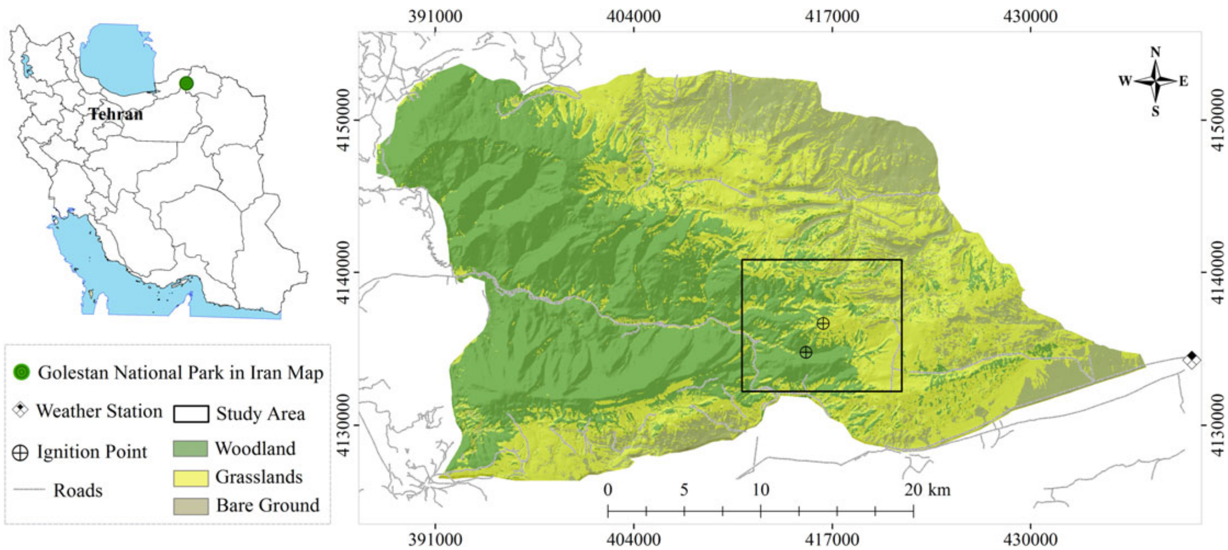

Figure 1 Location of the study area in southern Golestan National Park, Northeastern Iran. The black frame indicates the study area, where the YekeBermagh and Gharanghi fires were ignited.

YekeBermagh fire started on the 15 July 2011, lasted for 10 h, and was driven by a southwestern ∼22 km h^{-1} wind and burned 58 ha of grasses and Juniperus shrubland. Both fires spread over complex terrain and diverse vegetation types, through the valley bottom flat areas covered by grasslands, transitional edging shrublands and broadleaf forests on steep slopes.

Input data

The FARSITE and FlamMap fire modelling systems require the same set of gridded geospatial input data files for fire simulation. Landscape characteristics, weather conditions and fuel types of the study area are presented in Table 1. Topography (i.e. elevation, aspect and slope) and fuels (i.e. surface fuel type and canopy metrics) were assembled into a 10 m landscape grid file (LCP) of 9000 ha to simulate both fires (Figure 2). Canopy base height, canopy bulk density and canopy height are the forest canopy data input metrics that influence the crown fire initiation and propagation (Albini, 1976; Rothermel, 1991). The actual fires in the study area were surface fires and affected only surface layers. Therefore, spot fire growth was disabled setting the ignition frequency to 0 per cent (Table 1).

The digital elevation model (10 m; National Cartographic Centre of Iran, NCC) was used to generate the elevation, slope and aspect maps of the study area. Although there have been various efforts to map vegetation in Iran, these maps did not provide the necessary information required by the wildfire spread fire modelling systems. Hence, we generated the geospatial datasets regarding fuels characteristics (i.e. surface fuel models and canopy metrics) from data gathered in field inventories, based on the Line Transect method (Marshall *et al*., 2000;2003), and considering the 1:25 000 scale land-use land cover map (Department of Environment; Golestan; Iran, geo-statistics and Geographic Information Systems (GIS)) feature boundaries as reference. A set of 14 standard fuel models (Scott and Burgan, 2005) was assigned to the different land-use land-covers feature types (Table 1): GR4 and GR7 to grasslands; SH1 and SH2 on shrubby patches; TU1 and TU5 on woodlands with grass–shrub and litter mixed understorey; and TL2, TL6 and TL9 on broadleaf forests with timber litter, hardwood litter and litter and understorey.

Weather data were retrieved from the nearest weather station to the wildfire case studies, the Robate-GharehBil automatic weather station (1282 m a.s.l.; latitude 37°21′, longitude 56°19′), located at 20 km away from the east boundary of the park (Figure 1). For fire modelling with FARSITE, we generated an hourly weather dataset, from fire initiation to extinction, containing the information regarding temperature, relative humidity, wind speed, wind direction and rainfall (Table 1). On the other hand, since FlamMap assumes constant weather conditions for the whole fire event within a wildfire (Finney, 2006a), we used the wind speed and direction observed during the active fire spread period, when the most relevant fire runs and the burned area occurred (i.e. 21.6 km h^{-1} and 14.4 km h^{-1}, with 225° and 170° wind directions, for YekeBermagh and Gharangi fires, respectively).

The live woody fuel moisture content input data values were derived from other studies with similar Mediterranean ecosystems and vegetation types (Dimitrakopoulos, 2002; De Luis *et al*., 2004; Arca *et al*., 2007; Sağlam *et al*., 2008; Chuvieco *et al*., 2011; Table 1). The dead fuel moisture content was determined considering the methodology proposed by Rothermel (1983), where the dead fuel moisture content is estimated from the weather (ambient temperature and relative humidity), topography (elevation, aspect and slope) and vegetation (shading of surface fuels) condition data and Fire date (month and time of day) (Jahdi *et al*., 2015). In the both case studies, herbaceous type fuels were annual grasses that during the wildfire season peak are fully cured.

Fire modelling

We used FARSITE (Finney, 1998) and FlamMap (Finney, 2006a), MTT algorithm mode, to simulate YekeBermagh and Gharangi. FARSITE is a two-dimensional program for spatially and temporally simulating the spread and behaviour of fires under heterogeneous conditions (Stratton, 2006). FARSITE incorporates models for surface fire spread and behaviour simulation (Rothermel, 1972), crown fire initiation (Van Wagner, 1977;1993), crown fire spread (Rothermel, 1991), spotting (Albini, 1979), point-source fire acceleration (Finney, 1998), and dead fuel moisture (Nelson, 2000), that require information on fuels, weather and topography (as provided by the FARSITE landscape file (LCP)). Simulation outputs are in tabular, vector and raster formats. Unlike FARSITE, FlamMap makes independent fire behaviour calculations (e.g. fireline intensity and flame length) for each location of the raster landscape (cell), independent of one another and weather and fuel moisture content data are held constant. It uses the same spatial and tabular data and incorporates the same fire behaviour models as FARSITE.

Table 1 Landscape characteristics, fire weather conditions and inputs used for the fire simulations in both study areas

		Case study	
		YekeBermagh	Gharangi
Location		Latitude 37° 22′ N, Longitude 56° 03′ E	Latitude 37° 21′ N, Longitude 56° 02′ E
Topography	Elevation (m a.s.l.)	1930–2340	1330–1525
	Slope (°)	0–45	0–38
	Aspect	S	S
Main fuel type Scott and Burgan (2005) affected by the fire	(percentage and description; fuel models)	Grassland (82%, moderately coarse continuous grass; GR4 and GR7) and shrubland (18%, low and moderate load dry climate shrub; SH1, SH2)	Natural mixed forest (68%; low and very high load dry climate timber-grass-shrub; TU1, TU5) and natural pure forest (32%; low, moderate and very high load broadleaf litter; TL2, TL6 and TL9)
Fuel moisture content (FMC)	1 h dead FM (%)	5	13
	10 h dead FM (%)	6	14
	100 h dead FM (%)	8	16
	LH live FM (%)	0	75
	LW live FM (%)	GR = 0; SH = 70	100
Fire date (dd/mm/yyyy)		15/07/2011	28/03/2011
Burned area (ha)		58.06	10.04
Type of fire	–	Surface fire	
Average weather parameters during the timeframe of the fire spread	Temperature (°C)	22	11
	Relative humidity (%)	20	50
	Wind speed (km h^{-1})	21.6	14.4
	Wind direction	SW	SW
	Rain (mm)	0	0
Simulation resolution		10 m	
FARSITE model parameters	Time step	30 min	
FARSITE fire behaviour options	Spot fire growth	No	
	Ignition frequency	0%	

Fire growth simulations were performed at 10 m resolution. The simulation duration that establishes the starting and stopping times for the fire and fuel moisture calculations was 10 and 7 h, respectively, for YekeBermagh and Gharangi fires. For all simulations, the adjustment factor for fire rate of spread was set 1.0 for all surface fuel models. No suppression efforts were considered in fire modelling due to the lack of accurate information.

Both simulators were used to calculate the three basic fire descriptors for each fire event: burned area perimeters, rate of spread and fireline intensity. The rate of spread in the Rothermel (1972) model can be defined as the ratio between the heat received by unburned fuel and the heat required to ignite the unburned fuel, and is calculated as

$$\mathrm{ROS} = \frac{I_R \times \xi \times (1 + \Phi_W + \Phi_S)}{\rho_b \times \varepsilon \times Q_{ig}} \tag{1}$$

where ROS is the rate of spread (m min^{-1}), I_R is the reaction intensity (J $s^{-1}m^{-2}$), ξ is the propagating flux ratio, Φ_w is the wind factor, Φ_s is the slope factor, ρ_b is the fuel bed bulk density (kg m^{-3}), ε is the effective heating number, and Q_{ig} is the heat of pre-ignition (J kg^{-1}). The Rothermel equation computes the steady-state rate of fire spread in the direction of maximum fire spread and assuming that wind and slope are aligned in this direction.

Fireline intensity (FLI, kW m^{-1}) is determined from fire rate of spread and fuel consumption using Byram's (1959) equation:

$$\mathrm{FLI} = H \times w_a \times \mathrm{ROS}, \tag{2}$$

where H is the net low heat of combustion (kJ kg^{-1}), w_a is the fuel consumed in the active flaming front (kg m^{-2}), and *ROS* is the linear rate of fire spread (m s^{-1}). It is assumed that the fire spreads by a sequence of ignitions, where the heat produced from the flaming zone of the fire provides sufficient energy to ignite the adjacent unburned fuels (Dimitrakopoulos and Dritsa, 2003). Burned area predicted perimeters were drawn from the last burned pixel contour boundaries.

Statistical and graphical analysis

The accuracy in simulated fire perimeters was assessed by calculating Sorensen coefficient (SC; Legendre and Legendre, 1998) and Cohen's κ coefficient (KC; Congalton, 1991), which can range from 0 to 1. SC values were calculated as follows:

$$\mathrm{SC} = \frac{2a}{2a + b + c} \tag{3}$$

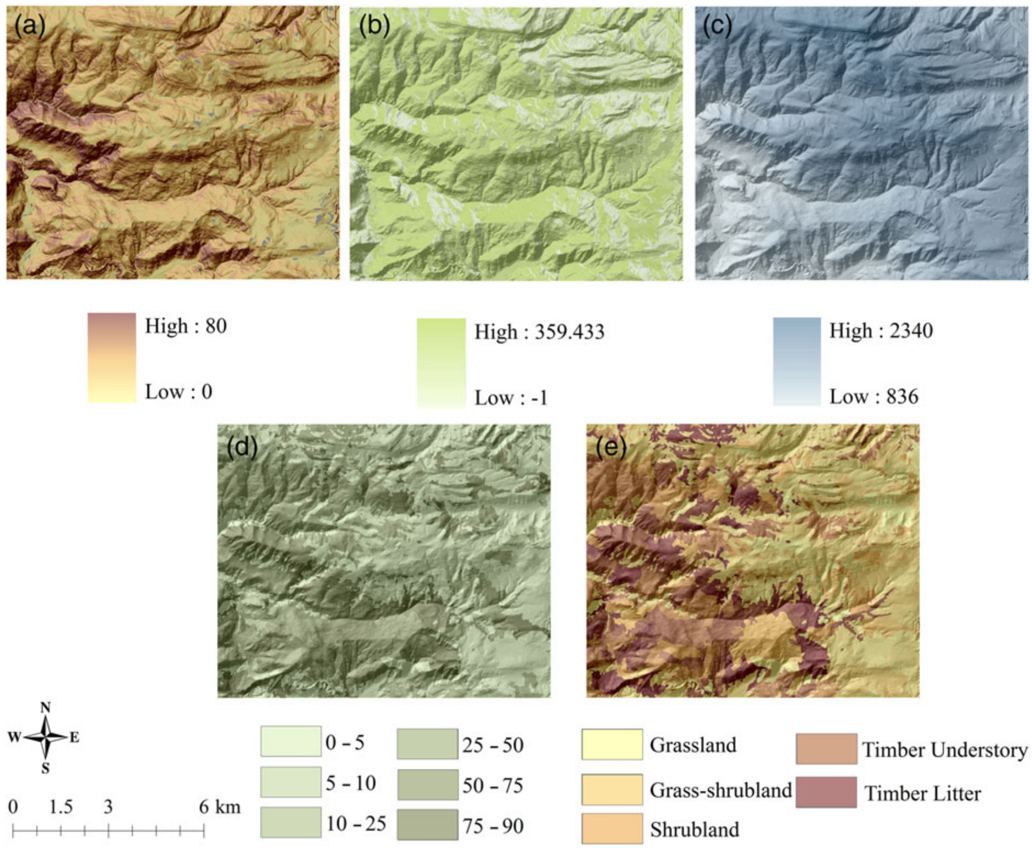

Figure 2 Maps of slope (degrees; a), aspect (degrees, b), elevation (meters; c), canopy cover (percent; d) and fuel types (e) used to generate the landscape file (LCP) layer of the study area (~9000 ha), with a resolution of 10 m.

where *a* is the number of cells coded as burned for both observed and simulated fires, *b* is the number of cells coded as burned in the simulation and unburned in the actual fire and *c* is the number of cells coded as unburned in the simulation and burned in the actual fire. KC values were calculated as follows

$$\mathrm{KC} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_1 + x + 1)}{N^2 - \sum_{i=1}^{r}(x_i + x + i)}, \tag{4}$$

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. SC is an indicator of the exclusive association between the burned areas (observed and simulated), and KC is a measure of classification accuracy and indicator of the overall agreement. The higher the SC and KC value, the higher is the accuracy in burned area estimates. In many other studies, SC and KC metrics have been used as well to assess the fire simulation accuracy (Perry *et al*., 1999; Arca *et al*., 2007; Salis, 2008; Peterson *et al*., 2009).

We first independently analyzed the accuracy of each model, and then we compared the differences between FARSITE and FlamMap MTT outcomes. In addition, we calculated SC and KC within the different fuel model types (i.e. grasslands, shrublands, mixed forests and conifer/broadleaf forests), and within six slope ranges (i.e. 0–5, 5–10, 10–15, 15–20, 20–25 and >30).

Finally, we used predicted rate of spread and fireline intensity maps to compare and analyze the spatial differences among the output values obtained with the different simulators. Regarding the FLI, the values were divided into four classes, according to surface fire suppression effectiveness interpretation charts (Andrews *et al*., 2011). To show the spatial differences in ROS and FLI outputs from FlamMap and FARSITE, we characterized pixel-level differences in the modelled burned area between the simulators.

Results

Burned area prediction accuracy

Overall, both fire simulators showed good agreement in predicting the observed fire perimeters, with $0.69 \geq \mathrm{SC} \leq 0.79$ and $0.68 \geq \mathrm{KC} \leq 0.79$ (Table 2), and in both case studies the results indicated that MTT perimeter simulations were slightly better compared with the FARSITE simulations (SC and KC ≤ 0.79 from MTT; SC ≤ 0.76 and KC ≤ 0.75 from FARSITE; Table 2). The differences between FARSITE and MTT in terms of SC and KC were very limited (SC and KC ≤ 0.08; Table 2) for both case studies. Both fire models overestimated the burned area in comparison with the observed fires, FARSITE in a greater extent than FlamMap, and mainly for the flank areas (Figure 3).

The area of the YekeBermagh fire was 58 ha, and both FARSITE and MTT simulations showed similar burned perimeters and overestimated the burned areas, respectively, of 30.75 and 21.66 ha (b;

Table 2 Evaluation of the FARSITE and FlamMap MTT models for the two case studies

Case study	Fire growth model	SC	KC	*a* (ha)	*b* (ha)	*c* (ha)	Wildfire area (ha)	Simulated area burned (ha)	Average ROS ± standard deviation (m min^{-1})	Average FLI ± standard deviation (kW m^{-1})
YekeBermagh	FARSITE	0.69	0.68	46.84	30.75	11.22	58.06	77.59	2.43 ± 1.29	277.86 ± 206.89
	MTT	0.77	0.76	49.45	21.66	8.61		71.11	2.81 ± 2.27	342.11 ± 350.36
	MTT *vs* FARSITE	0.75	0.74	55.59	22.00	15.41		–	–	–
Gharangi	FARSITE	0.76	0.75	7.48	2.23	2.56	10.04	9.71	0.51 ± 0.32	179.42 ± 147.94
	MTT	0.79	0.79	6.93	0.51	3.11		7.44	0.65 ± 0.49	219.78 ± 196.30
	MTT *vs* FARSITE	0.64	0.64	5.52	4.19	1.92		–	–	–

SC = Sorensen coefficient value; KC = κ coefficient value; *a* = area burned agreement; *b* = overestimation; *c* = underestimation.

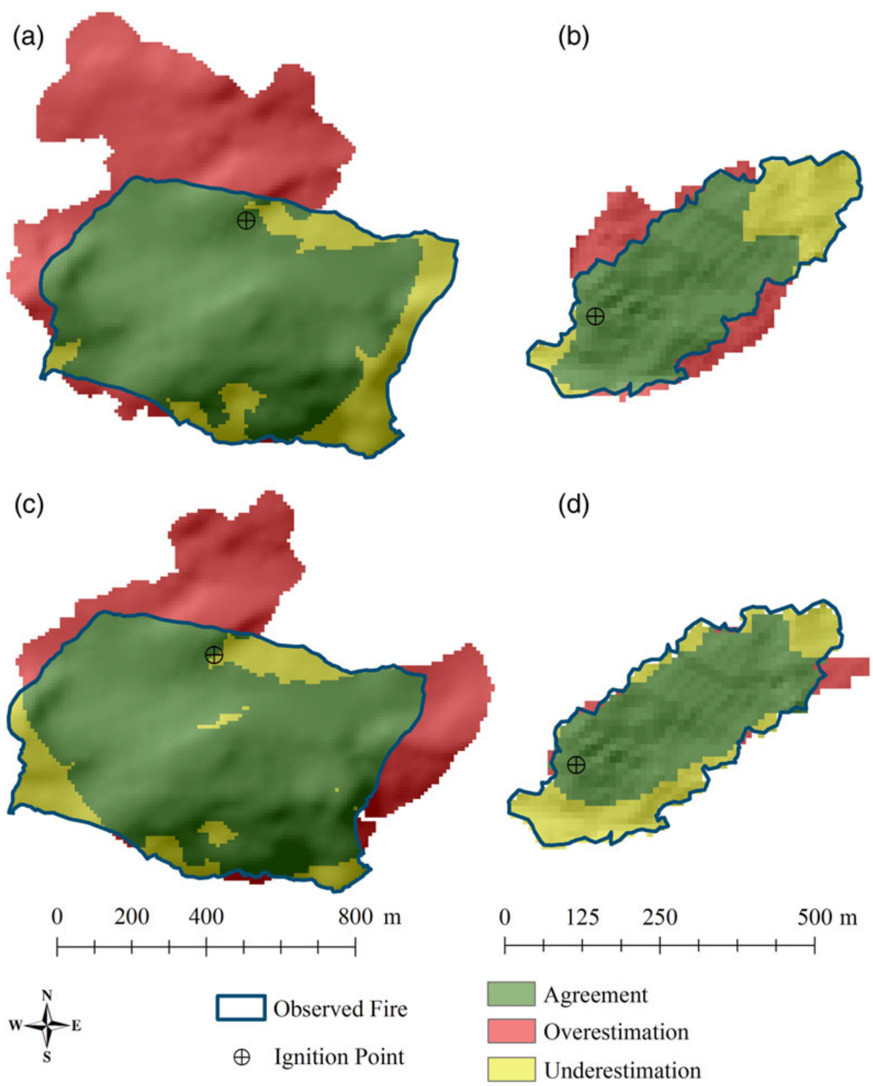

Figure 3 FARSITE simulation results for YekeBermagh (a) and Gharangi (b); and FlamMap MTT results for YekeBermagh (c) and Gharangi (d).

Table 2). Fire simulation results using both fire models and their differences are presented in Figures 3 and 4. Predicted area burned mainly overestimated the observed fire perimeters on the right flank and back fire area (Figure 3a,c), while small under-prediction was noticed on the heading fire spread area by both models. Based on the Sorensen coefficient values, the level of agreement between the real and simulated fire perimeters was 0.69 for FARSITE and 0.77 for the MTT (Table 2); the κ coefficient confirmed that MTT obtained better results than FARSITE (KC = 0.76 and KC = 0.68, respectively; Table 2). Comparing the total area burned by each simulator we found that FARSITE burned larger areas than MTT in heading-right flanking fire spread, while MTT simulation exceeded the FARSITE perimeter in the left flank (Figure 4a).

FARSITE and MTT simulations of the Gharangi fire generated fire perimeters of similar shape, and the size of the simulated fires using FARSITE and MTT was, respectively, ~9.71 and 7.44 ha (actual fire perimeter 10.04 ha). Results revealed that MTT simulation statistics (SC = 0.79; KC = 0.79; Table 2) were slightly better compared with the FARSITE ones (SC = 0.76; KC = 0.75; Table 2). The simulations obtained by both models provided a simulated burned area characterized only by a small overestimation and underestimation on both the fire front and flanks (<30 per cent underestimation and <20 per cent overestimation). MTT underpredicted the burned area in the back and heading fire spread, while the under-prediction of FARSITE was concentrated on the heading fire spread (Figure 3a,b). The comparison among the

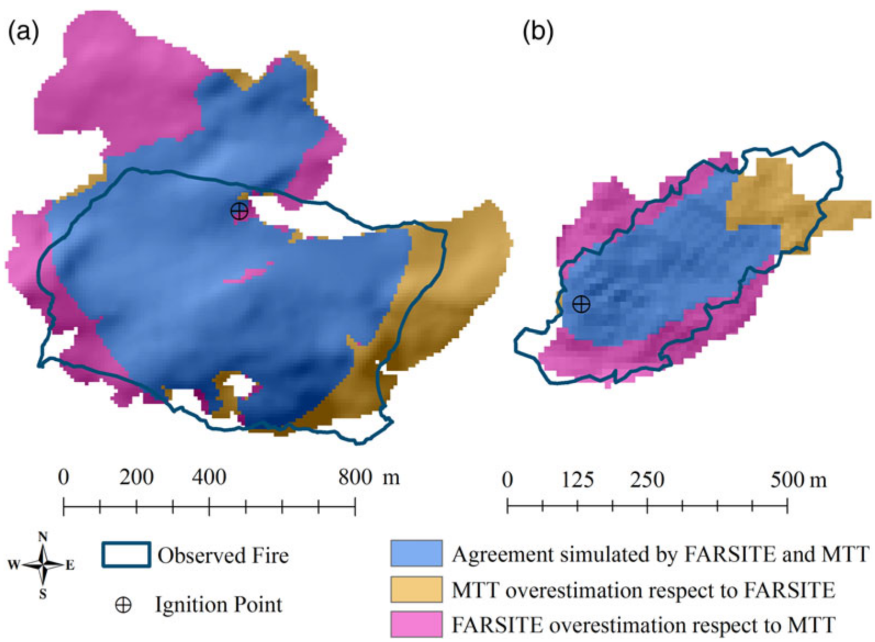

Figure 4 FlamMap MTT *vs* FARSITE simulation results for YekeBermagh (a) and Gharangi (b) fires.

Table 3 Evaluation of the FARSITE and FlamMap MTT models for individual fuel types in the two fires

Case study	Fire growth model	Fuel type	SC	KC	*a* (ha)	*b* (ha)	*c* (ha)	Wildfire area (ha)	Simulated area burned (ha)	Average ROS ± standard deviation (m min^{-1})	Average FLI ± standard deviation (kW m^{-1})
YekeBermagh	FARSITE	Grassland	0.73	0.70	42.05	19.93	5.82	47.87	61.98	2.60 ± 1.28	341.26 ± 265.52
		Shrubland	0.65	0.47	4.79	10.82	5.40	10.19	15.61	1.49 ± 1.63	248.52 ± 234.96
		Total	**0.69**	**0.68**	**46.84**	**30.75**	**11.22**	**58.06**	**77.59**	–	–
	MTT	Grassland	0.81	0.80	45.01	18.49	2.91	47.87	63.5	2.83 ± 2.47	372.11 ± 350.36
		Shrubland	0.53	0.53	4.44	2.10	5.70	10.19	6.54	1.53 ± 1.39	267.86 ± 286.89
		Total	**0.77**	**0.76**	**49.45**	**21.66**	**8.61**	**58.06**	**71.11**	–	–
Gharangi	FARSITE	Natural mixed forest	0.68	0.65	4.42	1.34	2.48	6.9	5.76	0.42 ± 0.39	185.55 ± 78.41
		Natural pure forest	0.84	0.84	3.06	0.89	0.08	3.14	3.95	0.36 ± 0.14	123.99 ± 64.38
		Total	**0.76**	**0.75**	**7.48**	**2.23**	**2.56**	**10.04**	**9.71**	–	–
	MTT	Natural mixed forest	0.85	0.85	4.67	0.31	1.3	5.97	4.98	0.69 ± 0.44	205.75 ± 115.23
		Natural pure forest	0.69	0.69	2.26	0.2	1.81	4.07	2.46	0.63 ± 0.29	149.43 ± 83.11
		Total	**0.79**	**0.79**	**6.93**	**0.51**	**3.11**	**10.04**	**7.44**	–	–

Bold values indicate total values in each case study.
SC = Sorensen coefficient value; KC = κ coefficient value; *a* = area burned agreement; *b* = overestimation; *c* = underestimation.

Table 4 Evaluation of the FARSITE and FlamMap MTT models for slope classes in the two fires

Case study	Fire growth model	Slope class (°)	SC	KC	*a* (ha)	*b* (ha)	*c* (ha)	Wildfire area (ha)	Simulated area burned (ha)
YekeBermagh	FARSITE	0–5	0.85	0.84	6.01	1.47	0.57	6.58	7.48
		5–10	0.68	0.65	16.95	12.59	3.28	20.23	29.54
		10–15	0.71	0.70	12.45	9.34	0.94	13.39	21.79
		15–20	0.68	0.67	5.74	4.46	0.94	6.68	10.2
		20–25	0.62	0.61	2.00	1.61	0.86	2.86	3.61
		25–30	0.59	0.59	2.12	1.07	1.82	3.94	3.19
		>30	0.51	0.51	1.57	0.21	2.81	4.38	1.78
		Total	**0.69**	**0.68**	**46.84**	**30.75**	**11.22**	**58.06**	**77.59**
	MTT	0–5	0.82	0.82	6.05	2.13	0.53	6.58	8.18
		5–10	0.78	0.78	17.75	7.78	2.48	20.23	25.53
		10–15	0.76	0.76	11.33	4.91	2.06	13.39	16.24
		15–20	0.75	0.75	5.57	2.70	1.11	6.68	8.27
		20–25	0.66	0.66	2.27	1.74	0.59	2.86	4.01
		25–30	0.69	0.69	2.91	1.54	1.03	3.94	4.45
		>30	0.77	0.77	3.57	0.86	0.81	4.38	4.43
		Total	**0.77**	**0.76**	**49.45**	**21.66**	**8.61**	**58.06**	**71.11**
Gharangi	FARSITE	0–5	0.96	0.96	0.13	0	0.01	0.14	0.13
		5–10	0.74	0.74	0.17	0.01	0.11	0.28	0.18
		10–15	0.67	0.67	0.48	0.10	0.38	0.86	0.58
		15–20	0.75	0.74	2.36	0.59	1.02	3.38	2.95
		20–25	0.79	0.79	2.23	0.74	0.45	2.68	2.97
		25–30	0.78	0.77	1.63	0.55	0.39	2.02	2.18
		>30	0.69	0.68	0.48	0.24	0.2	0.68	0.72
		Total	**0.76**	**0.75**	**7.48**	**2.23**	**2.56**	**10.04**	**9.71**
	MTT	0–5	0.00	0.00	0.00	0.00	0.10	0.10	0.00
		5–10	0.07	0.07	0.01	0.00	0.27	0.28	0.01
		10–15	0.46	0.46	0.30	0.12	0.58	0.88	0.42
		15–20	0.81	0.81	2.46	0.33	0.81	3.27	2.79
		20–25	0.86	0.86	2.02	0.03	0.65	2.67	2.05
		25–30	0.86	0.86	1.58	0.03	0.47	2.05	1.61
		>30	0.83	0.83	0.56	0.00	0.23	0.79	0.56
		Total	**0.79**	**0.79**	**6.93**	**0.51**	**3.11**	**10.04**	**7.44**

Bold values indicate total values in each case study.
SC = Sorensen coefficient value; KC = κ coefficient value; *a* = area burned agreement; *b* = overestimation; *c* = underestimation.

modelled burned areas showed a wider flank fire spread in FARSITE simulation, and conversely MTT simulation exceeded FARSITE spreading in heading fire (Figure 4b).

Analyzing differences for fuel models

A wide range of SC and KC values were obtained for the different fuel types (Table 3). The highest accuracy coefficient value for individual fuel type was obtained in the Gharangi fire for natural mixed forest (KC = 0.85), while the lowest value was observed for shrublands in YekeBermagh fire (SC = KC = 0.53) from MTT simulations. Grassland fuel model showed higher accuracy coefficient values than shrubland with both simulators. In forest fuel models the results showed different performances, FARSITE obtained better results in natural mixed forest, and conversely MTT obtained better results for natural pure forest.

Both models tended to overpredict the burned area of all the fuel types in the YekeBermagh fire. There was a large overprediction (∼20 ha; Table 3) in grassland fuel models for both fire models. In the natural mixed forest fuel type in the Gharangi fire the underestimation was higher than the overestimation. Besides, comparing the simulations accuracy by fuel type, differences in coefficient values between FARSITE and MTT were lower in YekeBermagh (SC ≤ 0.12 in shrubland; KC ≤ 0.10 in grassland; Table 3) than in Gharangi (SC ≤ 0.17 in natural mixed forest; KC ≤ 0.20 in natural pure forest; Table 3).

Analyzing differences for slope classes

Results suggest that in both case studies FARSITE had greater predictive accuracy on lower slope classes (SC ≥ 0.68 and KC ≥ 0.65 in slope class 5–10°; Table 4), showing the highest level of accuracy on the shallowest slope class of Gharangi fire (SC = KC = 0.96 >0.82; Table 4), while the lowest values were obtained in highest slope class of the YekeBermagh fire (SC = KC = 0.51). On the other hand, MTT did not present a similar trend between the

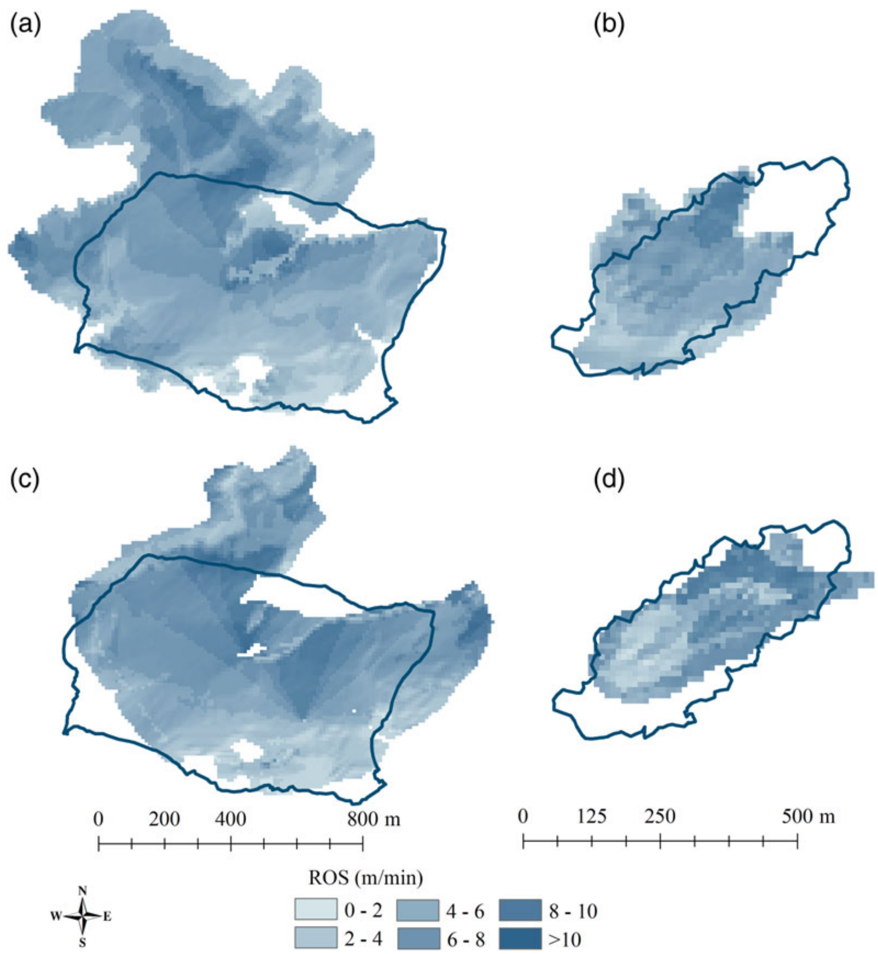

Figure 5 Comparison of the simulated ROS using FARSITE for YekeBermagh (a) and Gharangi (b) and using FlamMap MTT for YekeBermagh (c) and Gharangi (d).

slope class gradients for both simulations: in the YekeBermagh fire accuracy coefficient values were slightly higher on lower slope classes, while in the Gharangi fire obtained the best results for the highest slope classes (Table 4). The differences between the two fire models in terms of SC and KC in YekeBermagh area were limited (12 per cent; Table 3), but the differences in Gharangi area were significant (37 per cent; Table 3), for all the slope classes. Overall the differences among MTT and FARSITE in different slope classes were not large. We did not find clear trends in overestimation and underestimation result values for the different slope classes.

Rate of spread and fireline intensity

FlamMap MTT showed higher average values of ROS and FLI than FARSITE for both case studies (Tables 2 and 3; Figures 5 and 6). Natural mixed and pure forests (TU and TL fuel types) in the Gharangi area presented lower ROS and FLI values (0.36 – 0.69 m min^{-1} average ROS; 124 – 205.75 kW m^{-1} average FLI; Table 3) than grass and shrubland fuel types in the YekeBermagh study area (1.49 – 2.83 m min^{-1} average ROS and 248.52 – 372.11 kW m^{-1} average FLI; Table 3).

The spatial differences between FlamMap MTT and FARSITE for ROS output maps were overall limited (Figure 7).

In 70 per cent of the YekeBermagh case study, the differences of ROS resulted lower than 2 m min^{-1}. In 5 per cent of the simulated area burned (blue colour; Figure 7; mostly covered by shrubland), FlamMap MTT estimated lower ROS values than FARSITE, with differences ranging between 0.5 and 5 m min^{-1}. Only for <10 per cent of the case study (red colour; Figure 7; areas mostly covered by grasslands) the differences were quite relevant and ranged between 8.5 and 17.5 m min^{-1}.

Regarding the Gharangi wildfire, ∼45 per cent of the area burned (blue colour; Figure 7; mainly covered by natural pure forest) highlighted lower values of ROS for FlamMap MTT in comparison with FARSITE, while for the 55 per cent of the area (red colour; Figure 7; largely covered by natural mixed forest) FlamMap MTT estimated higher ROS values than FARSITE. Fire rate of spread and intensity were generally low in both TU and TL fuel types of the study area, and this is in agreement with firefighting reports and information.

Figure 8 shows the differences of the simulated FLI between FARSITE and FlamMap MTT. The second model estimated higher FLI values than FARSITE. For the case study of YekeBermagh, for ∼90 per cent of the area the differences between the models were lower than 700 kW m^{-1}. FlamMap MTT estimated lower FLI values than FARSITE (differences <20 kW m^{-1}) only for ∼15 per cent of the area (blue colour; Figure 8; covered by shrubland),

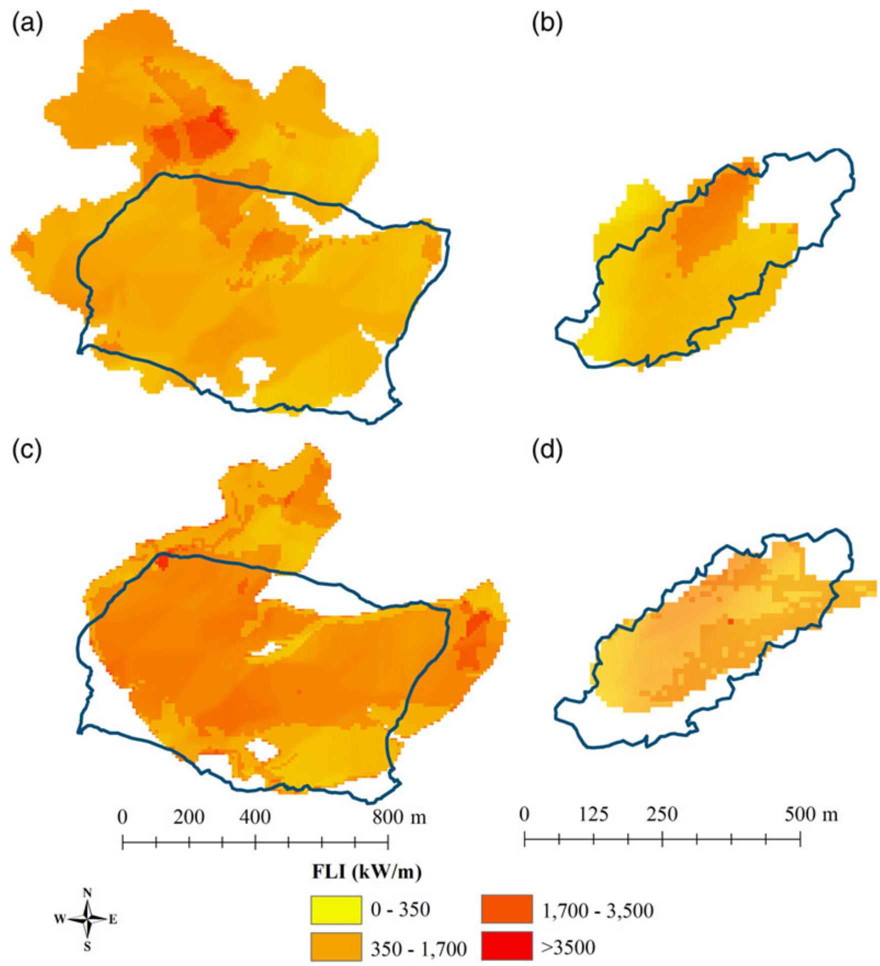

Figure 6 Comparison of the simulated FLI using FARSITE for YekeBermagh (a) and Gharangi (b) and using FlamMap MTT for YekeBermagh (c) and Gharangi (d).

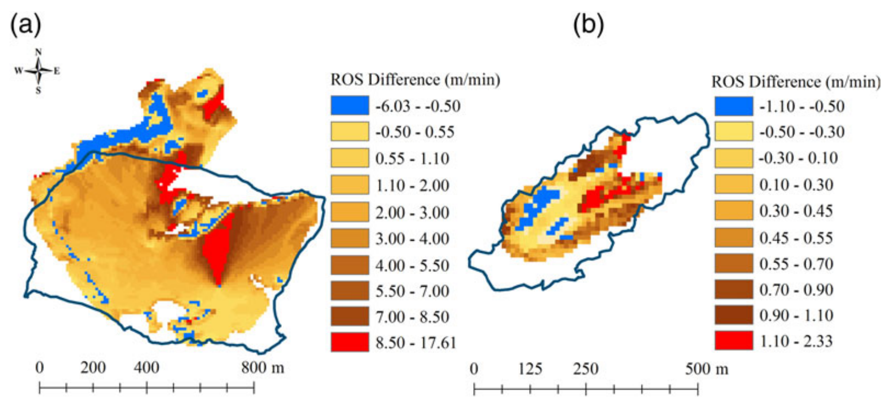

Figure 7 Maps of ROS difference between FlamMap MTT and FARSITE for YekeBermagh (a) and Gharangi (b) fires.

and in 5 per cent of the area (red colour; Figure 8; covered by grassland) FlamMap MTT estimated higher values than FARSITE with differences >900 kW m^{-1}.

In Gharangi, in 80 per cent of cases, the differences of FLI values between two models were lower than 200 kW m^{-1}. Also, in 15 per cent of cases (blue colour; Figure 8; covered by natural pure forest) FlamMap MTT estimated lower values than FARSITE, while in 10 per cent of cases (red colour; Figure 8; covered by natural mixed forest) FlamMap MTT estimated higher values than FARSITE.

Discussion and conclusions

A variety of programs and tools can nowadays support fire management helping to reduce uncertainty for fire prevention and

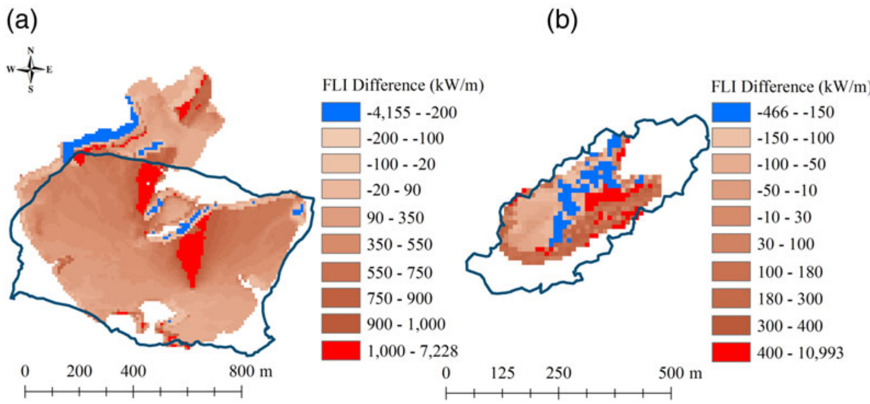

Figure 8 Maps of FLI difference between FlamMap MTT and FARSITE for YekeBermagh (a) and Gharangi (b) fires.

suppression and for prioritizing fuel treatments for fire risk mitigation. The numerous issues and limitations with the current fire modelling systems such as the lack of accurate input data need to be addressed in order to consider a broad array of fire management problems in different areas (Ager *et al*., 2011). Calibration of fire models with empirical data and sensitivity analyses should accompany all modelling efforts to help ensure appropriate application of the modelling tools in fuel management and wildfire risk assessment problems (Arca *et al*., 2007; Ager *et al*., 2011; Jahdi *et al*., 2015).

In this study, fire growth and behaviour patterns across complex landscapes using FARSITE and FlamMap MTT were compared. Such analyses can indicate where input data (i.e. fuels, wind, topography) are not able to provide realistic fire behaviour predictions. Both FARSITE and MTT simulations showed reasonable results for the YekeBermagh and Gharangi fires. Since both models replicate the spatial growth of fire perimeters using very similar approaches, this may explain the limited differences among the two fire models. The overprediction in the fire perimeters simulations by both fire models, especially in the YekeBermagh case study, and as also found in other fire modelling exercises (Arca *et al*., 2007; Alcasena *et al*., 2015), may reflect three factors: first, the Rothermel model may overpredict the rates of spread for the fuel models used (grassland and shrubland); secondly, inaccuracy and uncertainty of the input data such as fuel moisture content, wind data and fuel model assignments may result in incorrect fire propagation and behaviour values; thirdly, the lack of accurate information on fire extinction activities may cause overprediction in simulated areas. Overpredictions in backing and flanking fire areas were expected in both fires, and in those areas where the fire suppression activities have affected burned areas. The statistical evaluations of the performance of FARSITE and FlamMap MTT simulators in terms of SC and KC highlighted that the differences between the two fire models were limited for both case studies (Table 2). The differences between the models for the case study of YekeBermagh area were lower than Gharangi area (Tables 3 and 4).

Grasslands in the study areas are mostly tall and dense, with high fuel load, and consequently can release high amounts of energy when fire occurs. Our results confirm that the highest fireline intensity values were associated with the grassland fuel types (Figures 5 and 6). The lowest performances of both FARSITE and FlamMap MTT for Gharangi and YekeBermagh were observed for shrubland fuel types (Table 3), which in the study area have moderate-low fuel load. This suggests the need of further studies in north Iranian ecosystems and of the development of custom fuels for shrublands in the study areas, which are complex and largely variable in both spatial and temporal terms. Moreover, the research programs carried out up to date on fuels in Iranian ecosystems are very limited and did not map or quantify many fuel characteristics (i.e. fuel loading, surface-area-to-volume ratio, moisture of extinction and heat content). While many authors have emphasized the importance of using real and accurate information of fuels characteristics, especially the moisture content, ultimately determine fire behaviour, focussing on the critical fire areas. For instance, Ziel and Jolly (2009) highlighted the important role played by live herbaceous fuel moisture in determining fire behaviour in any dynamic fuel model with herbaceous load.' Investments in gathering fuel data will help assessing fire behaviour potential in the study area, which will increase the margin of safety for wildland firefighters in the future and will aid in operational planning for fire managers (Page *et al*., 2014).

As expected, we found strong differences among fuels and slope classes within the study areas. Regarding simulation of historic fire events in the study area, our work showed that overall FlamMap MTT achieved slightly better fire prediction results than FARSITE (Kalabokidis et al., 2014a; Petillo, 2014). Further field studies of actual fire spread and behaviour, especially studies involving large fires are necessary in order to validate and calibrate the outcomes of the fire behaviour simulators in the northern Iran vegetation conditions. Despite the discrepancies between observed and simulated final fire perimeters and behaviour, the results of our study indicate that the potential for operational application of the models is promising, particularly for wildfire prevention and management purposes.

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Conflict of interest statement

None declared.

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