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Evaluation of FARSITE simulator in Mediterranean maquis

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Abstract. In the last two decades, several models were developed to provide temporal and spatial variations of fire spread and behaviour. The most common models (i.e. BEHAVE and FARSITE) are based on Rothermel's original fire spread equation and describe fire spread and behaviour taking into account the influences of fuels, terrain and weather conditions. The use of FARSITE on areas different from those where the simulator was originally developed requires a local calibration to produce reliable results. This is particularly true for Mediterranean ecosystems, where plant communities are characterised by high specific and structural heterogeneity and complexity. To perform FARSITE calibration, an appropriate fuel model or the development of a specific custom fuel model is needed. In this study, FARSITE was employed to simulate three fire events in Mediterranean areas using different fuel models and meteorological input data, and the accuracy of results was analysed. A custom fuel model designed and developed for shrubland vegetation (maquis) provided realistic values of rate of spread, when compared with estimated values obtained using standard fuel models. Our results confirm that the use of both wind field data and appropriate custom fuel models are crucial to obtain reasonable simulations of wildfire events occurring on Mediterranean vegetation during the drought season.

Additional keywords: behaviour, fire modelling, fuel models, Mediterranean forest areas, shrubland vegetation.

Introduction

FARSITE (Fire Area Simulator, Finney 1998) is one of the main fire simulation systems developed over recent years to describe the spread and behaviour of wildland fires. The simulator is based on the semi-empirical fire prediction model developed by Rothermel (1972) and incorporated into the BEHAVE Fire Behaviour Prediction and Fuel Modelling System (Andrews 1986). As FARSITE is a spatially and temporally explicit model, it can produce detailed analysis of fire behaviour and fire effects (fire spread, fire-line intensity, burned area, etc.). To support these modelling capabilities, the simulator requires specific input layers (elevation, slope, aspect, fuels, percent canopy cover, etc.), consisting of georeferenced digital map data. The spatial growth of fire is simulated as elliptical wave propagation by applying the Huygens' principle (Richards 1990; Finney 1998). The actual physical characteristics of fuel bed (fuel load, fuel moisture, moisture of extinction, heat content, etc.) are approximated using a set of standard fuel models (Anderson 1982; Scott and Burgan 2005) or specific customised fuel models.

FARSITE was originally developed for long-range simulation of prescribed fires in US National forest, park and wilderness areas. Therefore, the simulator was extensively validated using a large database of fires occurring in those areas. Several studies in areas different from those where the models were originally developed followed, also validating both the Rothermel's model and the FARSITE simulator. Most of these studies were conducted in Europe and Australia (van Wilgen *et al*. 1985; Perry *et al*. 1999; Sauvagnargues-Lesage *et al*. 2001; Dimitrakopoulos 2002; Miller and Yool 2002; Bilgili and Saglam 2003; Pastor *et al*. 2003; De Luis *et al*. 2004). Some of the above-mentioned authors reported that calibration and validation of the simulator could be difficult when fuel characteristics and weather conditions were largely different from those used to calibrate and validate the original model.

Although Rothermel's model is based on the solution of the energy conservation equation (Rothermel 1972), it provides a good approximation of fire spread only within the range of conditions tested during the phases of model development and calibration (van Wagtendonk 1996; Zhou *et al*. 2005*a*). The model formulation was based on a series of laboratory experiments conducted using small size and homogeneous dead fuels. This approach allowed a good control of experimental conditions (fuel bed, wind, slope, etc.), but simulation results were often unrealistic due to the model assumptions and some experimental limitations. In addition, during the phase of field experimental tests, a limited number of species and fuels were used.

In the real world, the fuel is not a simple, continuous and homogeneous single layer. The transition between dead and live fuels and the ecophysiological characteristics of the different species affect the moisture content of fuel. Therefore, the fuel moisture content cannot be constant throughout the fuel bed, and it is not correct to consider the flame front in steady-state condition and the fire spread independent on the shape of the fire front (van Wagtendonk 1996; Finney 1998). Consequently, fire behaviour is difficult to estimate and the errors on the simulated fire spread can be compounded to produce a decrease of

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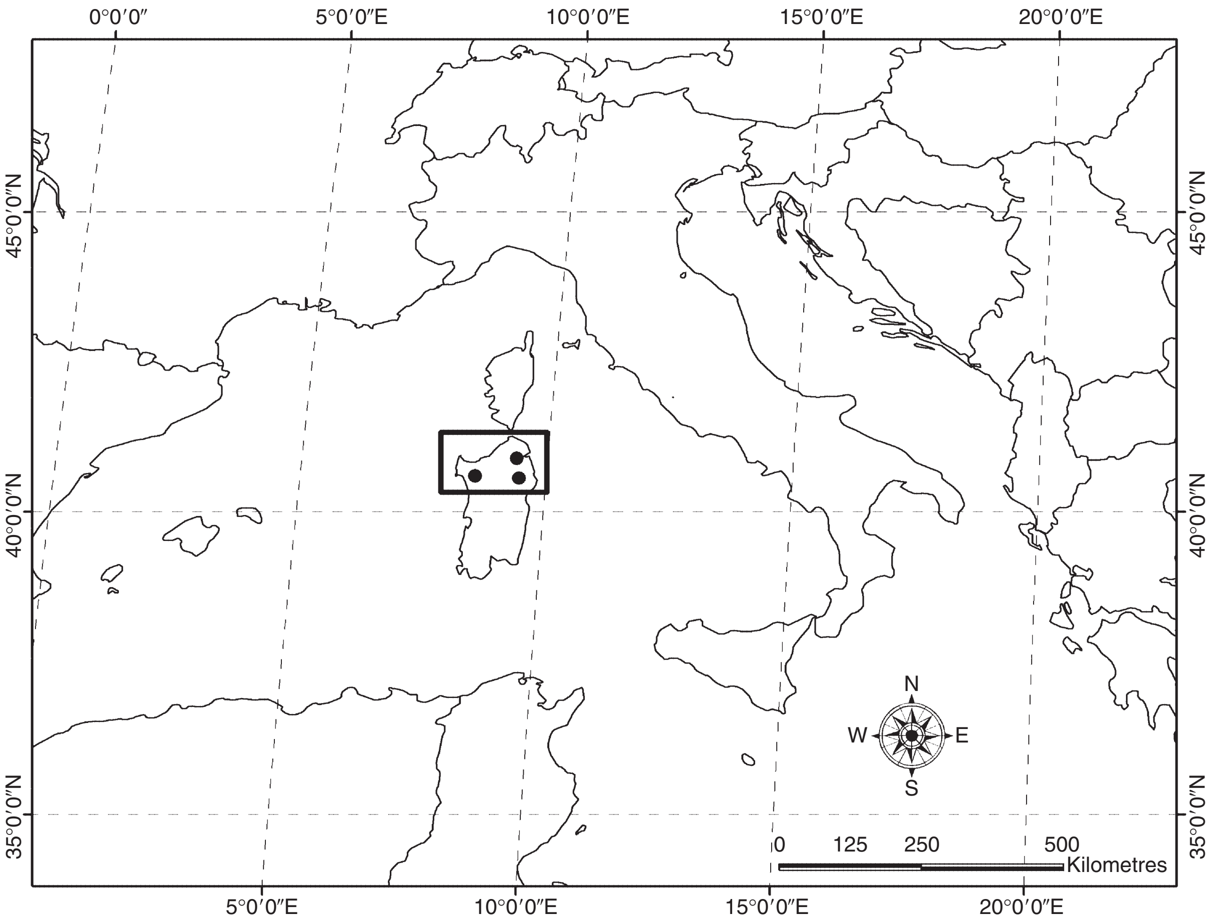

Fig. 1. Location of the three human-caused fire events occurred during the 2004 and 2006 drought seasons in North Sardinia (Italy).

accuracy, especially on large fires. The accuracy of simulations can be poor and the calibration process difficult (Albini and Baughman 1979; van Wagtendonk 1996; Andrews and Queen 2001; Fernandes 2001; Zhou *et al.* 2005*b*).

When Rothermel's model was used in Mediterranean climate areas, results were controversial (van Wilgen *et al.* 1985; Sauvagnargues-Lesage *et al.* 2001; Weise *et al.* 2005). This was attributed to the characteristics of shrubland vegetation across the Mediterranean Basin (i.e. high specific and structural heterogeneity and complexity). Unlike many other vegetation ecoregions, live fuel is the main component of the available fuel to fire in Mediterranean shrubland (Fernandes 2001; Dimitrakopoulos 2002; De Luis *et al.* 2004; Morvan and Dupuy 2004; Weise *et al.* 2005; Sun *et al.* 2006). Shrubland vegetation is usually more flammable than other vegetation types because of the low moisture content and the high concentration of volatile organic compounds, typical of most species (Dimitrakopoulos and Papaioannou 2001; Baeza *et al.* 2002; Zhou *et al.* 2005*a*, 2005*b*). In addition, Mediterranean shrublands can sustain high intensity fires within a few days after rainfall and when meteorological conditions are not particularly severe, with temperature not exceeding 27°C, and relative humidity often more than 45%. Moreover, most fire events of the Mediterranean Basin are short in duration, and occur in complex terrain areas where spatial variability of wind speed and wind direction is usually large. In general, realistic simulations of fire behaviour using FARSITE are affected by (i) the consistency and accuracy of weather input data, and (ii) the accuracy of the fuel models and the additional parameters required by the simulator.

The main aims of this study were (i) to evaluate the capabilities of FARSITE simulator in accurately modelling the fire spread and behaviour in Mediterranean areas; and (ii) to analyse the effect of fuel models, weather conditions, and topography on the simulations.

Materials and methods

Case studies

FARSITE was used to simulate the propagation and behaviour of three human-caused fires, which occurred in North Sardinia (Italy) during the 2004 and 2006 summer seasons (Fig. 1). All of the case study sites show similar climate and topographic characteristics. The climate is sub-arid with a remarkable water deficit from May through September, and most of the annual rainfall (~650 mm) occurs in fall and winter. The mean annual temperature is ~17°C, with summer season highs often ~30°C. The average wind speed is relatively high (~4 m s^{-1}) in both winter and summer seasons, with ~50–70% of the days showing

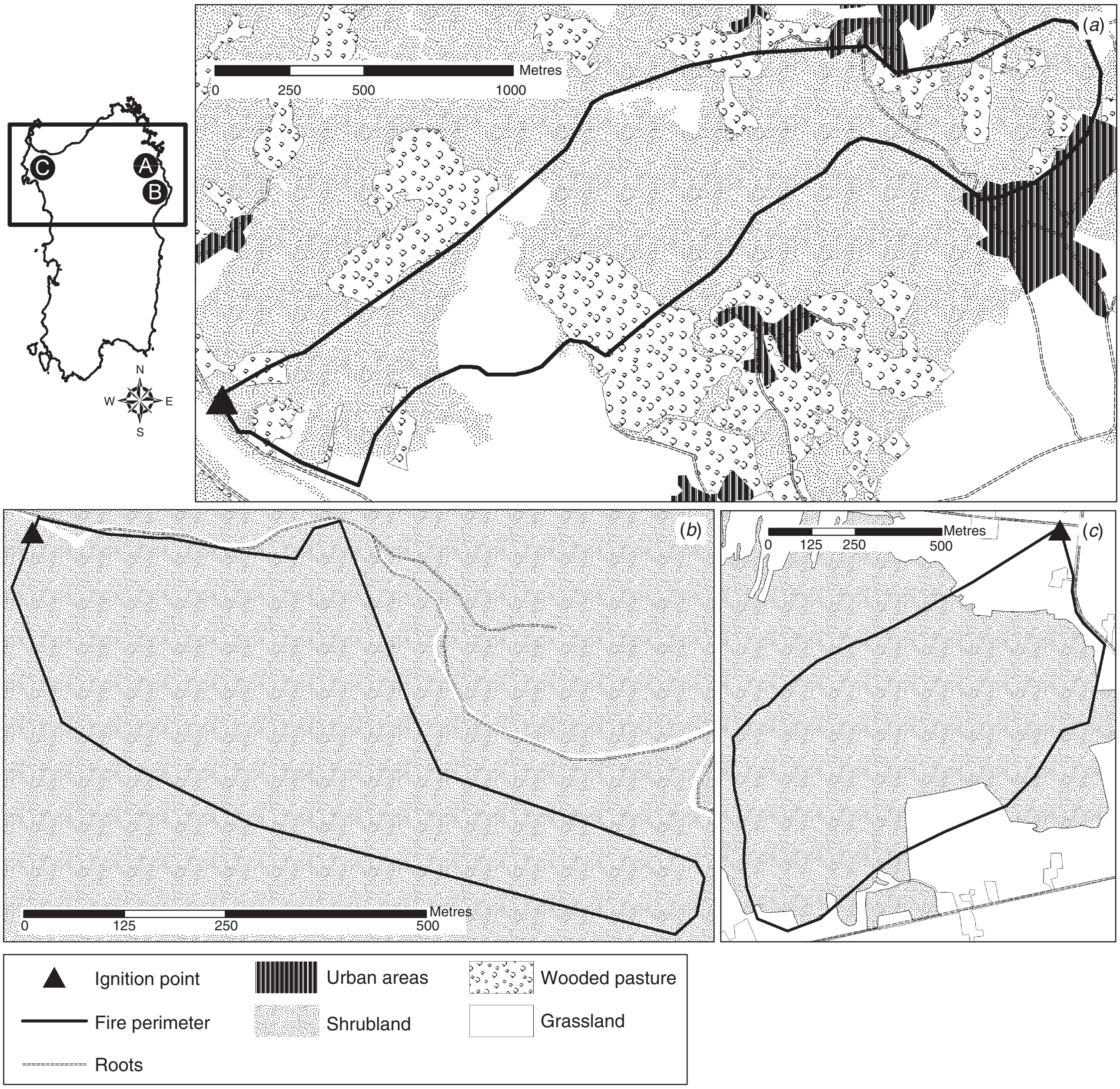

Fig. 2. Topographical map of the sites where the three human-caused fire events occurred: (*a*) Budoni, (*b*) Siniscola, and (*c*) Alghero. The three sites are located in North Sardinia, Italy. The map also illustrates the dominant vegetation covers: shrubland, wooded pasture, and grassland.

values between 1.6 and 8 $\mathrm{m\,s^{-1}}$. The prevailing wind directions at the sites are typically west and north-west, with a cumulative frequency greater than 50%. However, the local wind direction can be modified by the complex terrain typical of the studied areas.

The first fire occurred near the village of Budoni, Italy (40°43′N, 09°39′W, 50 m a.s.l.) in August 2004, in a hilly area where ~145 ha were burnt. The burned area (Fig. 2) was mainly covered by the typical shrubland Mediterranean vegetation (~104 ha), with plant height ranging from 1 to 4 m. Dominant species included *Olea europaea* L. var. *oleaster*, *Cistus monspeliensis* L., *Pistacia lentiscus* L., *Myrtus communis* L., *Calycotome spinosa* L., *Euphorbia dendroides* L. Link and *Pyrus amygdaliformis* Vill. Small surfaces inside the area were covered by open wooded pastures and grasslands with an extension of ~22 ha and 19 ha, respectively. The fire started on 26 August at 5:00 p.m. local solar time (LST) near a road along the western side of the area. The fire spread quickly, moving towards the east, driven by a strong western wind of ~36 $\mathrm{km\,h^{-1}}$ on average. The fire was successfully extinguished by the Forest Service firefighters only on the initial portion of the south flank, near the grassland area. On the opposite flank, near a ridgeline, the effect of the wind was reduced by the slope of terrain and the fire stopped to propagating. The steep terrain and the strong upslope wind did not allow direct suppression attack on the head of fire. Consequently, the spread rate of the fire front decreased significantly only after 9:00 p.m. LST, probably due to both down-slope wind flow and decreasing wind speed. However, the fire threatened some residential and resort areas on the south-east boundary.

The second fire occurred near the village of Siniscola, Italy (40°30′N, 09°41′W, 360 m a.s.l.) in August 2004, in an area of ~19 ha (23-km south of the Budoni fire event, Fig. 2) covered by a mixed, dense shrubland vegetation with homogeneous structural characteristics and mainly composed of *Arbutus unedo* L., *Myrtus communis* L., *Erica arborea* L., *Cistus monspeliensis* L., *Cistus salvifolius* L., *Olea europaea* L. var. *oleaster* and *Phyllirea angustifolia* L. The fire started on 21 August at 7:00 p.m. LST and lasted ~5 h and 30 min. Although the fire event occurred in late afternoon, the weather was relatively severe, with air temperature ~24°C and relative humidity ~35%. The wind blew from the west with a speed of ~18 km h^{-1}. The fire was successfully controlled by the Forest Service firefighters only along a road on the north flank. On the opposite flank and on the head of the fire, the steep terrain and the lack of roads did not allow a direct suppression attack. The spread of the fire decreased near the east ridge-line.

The third fire occurred in North West Sardinia, near Alghero, Italy (40°40′N, 8°17′W, 45 m a.s.l.) in July 2006. The burned area (~67 ha, Fig. 2) was mainly covered (~58 ha) by dense shrubland vegetation predominantly composed of *Pistacia lentiscus* L., *Chamaerops humilis* L., and *Myrtus communis* L. A small area (~9 ha) on the north-east side was covered by grassland. The fire started on 15 July 2006 at 2:30 p.m. LST near a road along the north-east side of the area that ultimately burned. The fire lasted ~5 h and 30 min. The fire moved towards the south-west driven by a moderate north-east wind (with an average value of ~11 km h^{-1}). In general, weather conditions were favourable for fire propagation, with air temperature ~35°C and relative humidity ~30%. The fire was successfully controlled only on the central portion of the south flank, close to the grassland area.

The final surface extensions of the burned areas were determined by the Sardinian Forestry Corps (SFC) using a Global Positioning System (GPS) survey. In addition, the partial fire perimeters of the first case study were reconstructed using SFC information and interviewing witnesses.

FARSITE simulations

Several themes were acquired and managed using Geographic Information Systems (GIS) (ArcGIS 9, ESRI Inc., Redlands, CA, USA) to obtain the input layers needed to run the FARSITE simulations. The grid resolution of all spatial information was 15 m. A digital elevation model (DEM) was used to produce the maps of slope and aspect.

Hourly meteorological data (air temperature (T), relative humidity (RH), wind speed (U), wind direction (W), solar radiation (Rs), and rainfall (P)) were obtained from weather stations of the Sardinian Agrometeorological Service (SAR) network. The relative shortwave radiation (i.e. the ratio between solar radiation and extraterrestrial radiation) was used to define cloud cover conditions (Colliver 1991). As the relative shortwave radiation was always above the 0.60 threshold, cloud cover (CC) was assumed equal to 0 throughout the day (Aubinet 1994).

Meteorological data were input as daily values with the exception of U, W, and CC, which were input as hourly data provided as an ASCII format data stream. Additional FARSITE simulations were done using wind maps in raster format to determine the effect of wind field data on the accuracy of simulations. Wind speed and wind direction data were collected using a portable instrument (mod. MPM2000, Solomat Corp., Stamford, CT, USA) to simulate the effect of the topography (ridge-top, side-slope and valley bottom) on the wind regime that prevailed during each event. The wind maps were interpolated using the Inverse Distance Weighted method, as incorporated into ArcGis 9.1 (Watson and Philip 1985).

Fuel and canopy cover maps were produced by supervised classification of pre-fire aerial photographs (1 : 10000), field observation of the plant community, and use of the 1 : 25000 land cover map of Sardinia from the CORINE project (EEA 2002).

Several simulations were run using three standard fuel models for shrubland vegetation and two for wooded pasture and grassland. Model 4 by Anderson (FM4), and models 145 (SH5) and 147 (SH7) by Scott and Burgan (Anderson 1982; Scott and Burgan 2005) were used for shrubland vegetation. A custom model named Custom Model Maquis (CM28) was developed and tested to account for the site specific vegetation cover, which represents one of the most common natural vegetation type of Sardinia, covering about 14% of the total surface area. The parameters of CM28 were defined using data from previous studies conducted in North Sardinia and in the Mediterranean Basin on similar vegetation types (Fernandes 2001; Baeza *et al*. 2002; Pellizzaro *et al*. 2003, 2005; De Luis *et al*. 2004). The initial values of fuel moisture content (FMC) for the 10-h time lag (TL) dead fuel were determined calculating the relationship between FMC (direct measurements) and fuel moisture sensor (model CS505, Campbell Sci., Logan, UT, USA) measurements obtained during days with meteorological conditions similar to those when the fire events occurred. The 1-h and 100-h TL dead fuel moisture content values were obtained from field observations and literature data (Fernandes 2001; Baeza *et al*. 2002; De Luis *et al*. 2004). Grassland and open wooded pasture covers were assigned to fuel models 1 (FM1) and 2 (FM2), respectively (Anderson 1982). In addition, the urban areas and roads were assigned to fuel model 91 (NB1, Scott and Burgan 2005). Table 1 shows the main characteristics of each fuel model.

Time step (20 min), perimeter, and distance resolution (20 m) were set up to obtain the expected spatial and temporal resolution of simulations. Fire suppression activities were simulated by the ground attack tool of the simulator using information provided by the Forest Service firefighting.

Statistical analysis

Several simulations were conducted to compare the performance of the FARSITE simulator when different combinations of fuel models and input parameters were used (Table 1). The output parameters provided by FARSITE were the fire perimeter for each time step, the fire time of arrival for each point of the grid, the rate of spread, and the fire-line intensity. Each output was in vector or raster format.

Table 1. Input variables and parameters of standard and custom fuel models used to run the FARSITE simulations of the three human-caused fire events occurred in North Sardinia in 2004 and 2006

Standard fuel models include FM1, FM2, FM4, SH5 and SH7. CM28 is the custom fuel model designed and developed for maquis vegetation presented in this study

Fuel mode code	FM1	FM2	FM4	SH5	SH7	CM28
Vegetation	Grass	Wooded pasture	Shrub	Shrub	Shrub	Shrub
Fuel model parameters						
– Dead fuel load (Mg ha^{-1})	1.66	7.84	24.70	12.78	24.66	9.86
1-h	1.66	4.48	11.23	8.07	7.85	3.92
10-h	0	2.24	8.99	4.71	11.88	3.92
100-h	0	1.12	4.48	0	4.93	2.02
– Live fuel load (Mg ha^{-1})	0	1.12	11.23	6.50	7.62	17.93
Herbaceous	0	0	0	0	0	0
Woody	0	1.12	11.23	6.50	7.62	17.93
Fuel model type	Static	Static	Static	Static	Static	Static
– Dead 1-h SAV (cm^{-1})	114	98	65	24	24	60
– SAV live herbaceous (cm^{-1})	59	59	59	59	59	0
– SAV live woody (cm^{-1})	49	49	49	52	52	50
– Fuel bed depth (cm)	30.48	30.48	182.88	182.88	182.88	200
– Moisture of ext. (%)	11	14	20	14	14	25
Dead heat content (kJ kg^{-1})	18 620	18 620	18 620	18 620	18 620	18 620
Live heat content (kJ kg^{-1})	18 620	18 620	18 620	18 620	18 620	18 620
Fuel moisture (%)						
– Dead fuel (%)						
1-h	5	5	8	8	8	8
10-h	8	8	11	11	11	11
100-h	12	12	13	13	13	13
– Live fuel (%)						
Live herbaceous	0	0	0	0	0	0
Live woody	0	100	60	60	60	60
Adjustment	1.0	1.0	1.0	1.0	1.0	1.0

The final fire surface area provided by FARSITE in vector format was transformed into raster format and reclassified as burned and unburned areas, in relation to the whole extension of each case study. The same procedure was applied on the actual burned areas. An error matrix between actual and simulated fire areas was calculated to define the frequency of each case (presence/absence of burned areas). The accuracy of each simulation was evaluated using two statistical indicators derived from the error matrix – Cohen's kappa coefficient (Congalton 1991; Congalton and Green 1999) and the Sørensen coefficient (Legendre and Legendre 1998).

Cohen's kappa coefficient (K) is a standard nonparametric measure of the classification accuracy, which allows for the evaluation of the overall agreement between simulated and actual areas after random agreements by chance are removed. K values were calculated as follows:

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

where r is the number of rows in the matrix, x_{ii} is the number of observations in row i and column i, x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively, and N is the total number of observations. K values typically range between zero and one, with values closest to one indicating highest agreement. The Z-test was used to determine (i) the overall accuracy values exceeding those obtained from chance agreement (Congalton and Green 1999); and (ii) the significance of the differences in K values among the simulations (Congalton and Mead 1983).

The second statistical index derived from the error matrix was the Sørensen coefficient (SC), an asymmetric index that is an indicator of the exclusive association between the burned areas (observed and simulated). SC values were calculated as follows:

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

where a is the number of cells coded as burned in both observed and simulated data, b is the number of cells coded as burned in the simulation and unburned in the observation, and c is the number of cells coded as unburned in the simulation and burned in the observation. The significance of the association was determined using the frequencies from the error matrix, and calculating the χ^2 statistic to test the null hypothesis of independence between observed and simulated areas (Ludwig and Reynolds 1988).

Moreover, the actual rate of spread (ROS) for the partial extent of the burned surfaces was estimated dividing the vector amplitude (L) from one perimeter to the next by the time (T) needed to move from the first to the second perimeter (ROS = L/T, m min^{-1}). ROS values for each fire event were estimated computing the sum of both L and T over the entire duration of each fire and then dividing the sum of L by the sum of T.

Results

The statistics and variables used to illustrate the simulation performances are reported in Table 2. The statistics showed that the best performance was obtained in all the case studies with simulation four performed using the custom fuel model CM28, which takes into account the specific characteristics of maquis. Cohen's kappa coefficient (K) values show that all simulations estimated the spatial extension of burned and unburned areas better than the random change at $P \leq 0.01$, with the exception of simulation one (FM4) of the second fire event (Siniscola), where a significant value of K (0.03) was obtained at P of 0.05 (Table 2). Simulation four (CM28) provided the best values of K, which ranged from 0.61 to 0.82. The other simulations (standard fuel models FM4, SH5, and SH7) gave K values ranging from 0.03 to 0.38.

A comparison of the K values obtained from the different simulations was done using the Z-test. Results showed that all the differences among the simulations were significant at $P \leq 0.01$, confirming, however, that the best performance was given by simulation four (Table 2). Comparing the standard fuel models, the higher K values were obtained using the SH7 model (simulation three), with values of K ranging from 0.27 to 0.38. The worst performances were provided by the model FM4 (simulation one), with K values ranging from 0.03 to 0.20 due to a systematic overestimation of the actual burned area. Our experimental results did not show site specific differences, indicating that CM28 can give good performances when the variability among sites in fuel and weather conditions is low.

The Sørensen coefficient (SC) was used as an indicator of the exclusive association between the burned areas (actual and simulated). The SC values showed in Table 2 confirmed the above-mentioned results. Although all simulations gave significant values of association at $P \leq 0.01$ using χ^2 test, the best agreement between observed and simulated burned areas was obtained using simulation four (SC = 0.72 ÷ 0.84). Simulations one, two and three always showed values less than 0.52. FM4 and SH5 fuel models (simulations one and two, respectively) showed the lowest SC values, especially in the case of the fire event occurred in Siniscola (SC = 0.11 ÷ 0.24).

The rate of spread (ROS) gives general information on the combined effect of fuel and environmental conditions on fire behaviour. Again, as reported in Table 2, the best agreement between actual and simulated ROS was obtained by simulation four, which slightly overestimated the actual values of ROS at Siniscola and Alghero. In general, the simulations performed using standard fuel models greatly overestimated the actual values of ROS, and the worst performance was obtained at Siniscola and Alghero.

As SC is an indicator of the exclusive association between the observed and simulated burned areas, it is also useful to compare model performances at different time steps. Due to the large amount of information available for the fire event that occurred at Budoni on August 2004, the comparison of model performances at different time steps was made using only simulation four at the Budoni site. Performances were evaluated calculating the SC values for three partial time steps (i.e. for three different burning periods): +2 h, +3 h and 30 min, and +6 h and 30 min from the starting time. Table 3 shows the good agreement between the actual and the simulated burned surface extensions for both the first (SC = 0.70) and the second time step (SC = 0.81), with a clear decrease of the coefficient value (SC = 0.63) during the third time step. The good performance obtained during the first time step, when the burned area was mainly covered by shrubland vegetation (87%), was confirmed during the second burning period, when a large burned surface was covered by grasslands (24%) and open wooded pastures (17%). During the third burning period, the accuracy of the simulation was probably reduced by the decrease in the intensity of wind speed and down-slope

Table 2. Statistical evaluation of FARSITE simulator performance by site and different combinations of fuel models. Two statistical indicators derived from the error matrix, the Cohen's kappa coefficient (K) and the Sørensen coefficient (SC) were used to determine the accuracy of each simulation. The mean values of the observed and simulated rate of spread (ROS) are also reported

*$P \leq 0.05$; **$P \leq 0.01$; values of K followed by the same letters are not significantly different at $P \leq 0.01$ by Z-score test; SC values followed by ** indicate a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test

Case study	Simulation/fuel model codes	K	SC	Observed ROS (m min^{-1})	Simulated ROS (m min^{-1})
A – Budoni	1 (FM4, FM1, FM2)	0.20^{**,A}	0.47**	8.1	22.3
	2 (SH5, FM1, FM2)	0.23^{**,B}	0.49**		20.7
	3 (SH7, FM1, FM2)	0.27^{**,C}	0.52**		16.7
	4 (CM28, FM1, FM2)	0.61^{**,D}	0.72**		8.1
B – Siniscola	1 (FM4, FM1)	0.03^{*,A}	0.11**	2.9	11.5
	2 (SH5, FM1)	0.17^{**,B}	0.24**		8.5
	3 (SH7, FM1)	0.38^{**,C}	0.42**		6.2
	4 (CM28, FM1)	0.80^{**,D}	0.81**		2.7
C – Alghero	1 (FM4, FM1)	0.18^{**,A}	0.34**	4.3	14.1
	2 (SH5, FM1)	0.23^{**,B}	0.38**		12.9
	3 (SH7, FM1)	0.33^{**,C}	0.45**		11.2
	4 (CM28, FM1)	0.82^{**,D}	0.84**		4.0

wind conditions. Simulation four, using raster maps of wind field and constant wind field, did not show relevant differences in SC values during the first and second time steps (Table 4), when a strong upslope wind propagated the fire. The simulation obtained using raster maps showed better results than a constant wind field value during the third time step, when the complexity of the terrain greatly affected local wind conditions (Table 4; Fig. 3).

Table 3. Values of the Sørensen coefficient (SC) from simulation 4 (custom fuel model CM28) by each partial time step of the fire event occurred in Budoni, Italy, on 26 August 2004

The SC value for the whole surface area is also shown. All SC values showed a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test

Time step	SC
1	0.70
2	0.81
3	0.63
Whole area	0.72

Table 4. Values of the Sørensen coefficient (SC) from simulation 4 (custom fuel model CM28) using raster maps of wind field and constant wind field for the fire event occurred in Budoni, Italy, on 26 August 2004

SC values for the whole surface area are also shown. All SC values showed a significant association between burned and unburned areas at $P \leq 0.01$ by χ^2 test

Time step	Wind maps	Constant wind field
1	0.70	0.71
2	0.81	0.81
3	0.63	0.48
Whole area	0.72	0.62

Observed ROS ranged from 7 to 12.4 m min^{-1} for the first and second time step, respectively, with a lower value (6.6 m min^{-1}) for the third burning period (Table 5). The estimated mean values of ROS were in agreement with the actual mean value for the first and third time step, with an underestimation of ~2.1 m min^{-1} for the second burning period. Fig. 4 shows the spatial variation of the simulated ROS. The maximum ROS values (42–56 m min^{-1}) were reached in a small area of the second time step. This was probably due to the combined effect of the steepness of terrain, the fuel type (open wooded pasture), and the limited effect of canopy cover reducing the strong upslope wind speed. The lowest values of simulated ROS (<9 m min^{-1}) were obtained for the areas covered by maquis, and intermediate values were observed when the cover consisted of open wooded pasture, and short and sparse shrubland vegetation.

Discussion and conclusion

In this paper, the performances of FARSITE simulator in a Mediterranean area where shrubland vegetation is predominant

Table 5. Observed and estimated rate of spread (ROS, m min^{-1}) from simulation 4 (custom fuel model CM28) by each partial time step of the fire event occurred in Budoni, Italy, on 26 August 2004. ROS values for the whole area are also shown

Time step	Observed ROS	Simulated ROS
1	7.0	6.5
2	12.4	10.3
3	6.6	7.4
Whole area	8.1	8.1

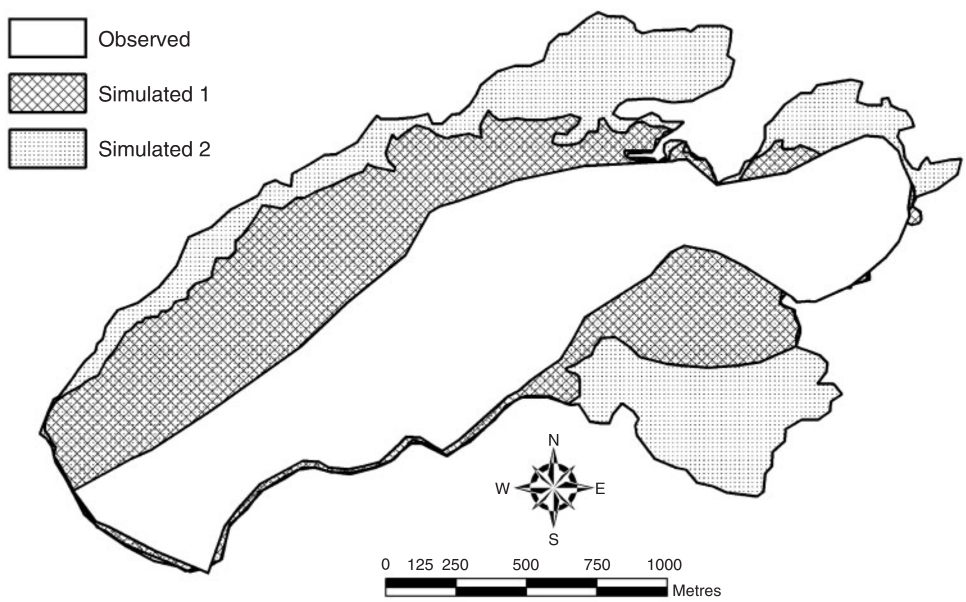

Fig. 3. Fire event in North Sardinia at Budoni, Italy, on 26 August 2004: comparison between observed and simulated fire areas from simulation 4 (custom fuel model CM28) using raster wind maps (Simulated 1) and constant wind field (Simulated 2).

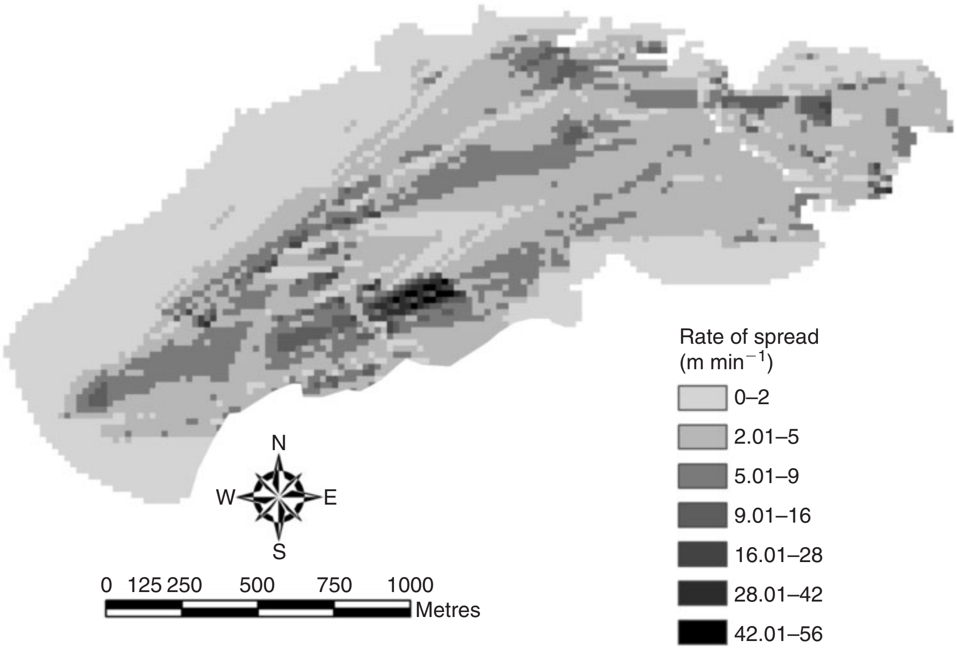

Fig. 4. Rate of Spread (ROS, m min^{-1}) predicted by simulation 4 (CM28) for the fire event that occurred in Budoni, Italy, on 26 August 2004.

were evaluated. The accuracy of FARSITE was improved using a custom fuel model (CM28) designed and developed with the purpose of simulating the spread rate and behaviour on this type of vegetation. The custom fuel model presented here is characterised by a higher live to dead fuel ratio, in comparison with the standard fuel models FM4 by Anderson (1982), and SH5 and SH7 by Scott and Burgan (2005), and includes a more balanced combination of the 1-h, 10-h and 100-h dead fuel loads. As reported by other authors (van Wilgen *et al*. 1985; Dimitrakopoulos 2002), our results suggest that a specific custom model needs to be developed to account for both the fuel characteristics and the high heterogeneity of shrubland vegetation. Weise and Regelbrugge (1997) reported an overestimation of actual fire spread in chaparral using the standard fuel model FM4, demonstrating that the accuracy of the simulation can be improved by developing and using a specific custom fuel model. van Wilgen *et al*. (1985) suggested the development of different custom fuel models to accurately describe the heterogeneous structural types of fynbos.

The parameters of our custom fuel model are in agreement with several studies conducted to determine the fuel types of Mediterranean vegetation. In relation to the distribution of fuel load on different size classes (1, 10 and 100 h), Dimitrakopoulos (2002) described the characteristics of two Mediterranean shrubland (maquis) fuel models, indicating that the 10-h and 100-h fuel load were significantly represented. In addition, Baeza *et al*. (2002) showed the effect of plant age on the fuel load in large size classes. As reported by Sun *et al*. (2006) for chaparral fuel, dead and live vegetation show differences in burning characteristics. In addition, the authors emphasised the importance of determining the effect of live chaparral on fire behaviour. Dimitrakopoulos and Papaioannou (2001) classified the foliage of the same species studied here as moderate flammable and flammable, even at high values of live moisture content. In addition, they showed the relevance of the relation between moisture of extinction and presence of essential oils, which are important factors in propagating the fire when plant moisture content is high. The effect of essential oil concentration on live vegetation fire spread was also reported in previous studies (Pyne 1984; Wilson 1985).

Several authors discussed the use of Rothermel's fire spread model in Mediterranean areas. Zhou *et al*. (2005*b*) did not recommend the use of this model in Mediterranean ecosystems (i.e. chaparral), because of the predominance of live fuel. Limitations of the Rothermel's model are particularly clear under low or moderate environmental conditions, typical of marginal burning (Zhou *et al*. 2005*a*). When more severe or extreme environmental conditions occur, the behaviour of fire is less affected by the fuel status and mainly depends on fuel type, weather, and slope conditions. In these conditions, the intrinsic limitations of Rothermel's model can be overcome by the use of both appropriate custom fuel models and accurate weather data, which are essential to obtain reasonable simulations of fire spread and behaviour. In our work, the FARSITE simulator combined with custom fuel model CM28 gave realistic values of rate of spread, similar to those reported by other authors for Mediterranean shrubland (Weise and Regelbrugge 1997; Fernandes 2001). Our results confirm that the performance of the FARSITE simulator is affected by the resolution and accuracy of wind data (Hanson *et al*. 2000). Improvements to the simulation accuracy could be obtained using high-resolution wind field data, calculated by computational fluid dynamics models

(Kim *et al*. 2000; Lopes *et al*. 2002; Lopes 2003; Butler *et al*. 2005).

In conclusion, the use of both wind field data and appropriate custom fuel models are essential to obtain reasonable simulations of fire spread and behaviour on Mediterranean vegetation during the drought season, when most of the annual wildfires occur. Information derived from databases of actual fires that occurred in Mediterranean areas could improve the accuracy of estimates by an extensive calibration and validation of the simulator. Further studies should be conducted to analyse the effect of the limitations and assumptions of Rothermel's model on the simulation accuracy, and to evaluate the potential of the FARSITE simulator in planning the operational phases of fire management in Mediterranean Basin areas.

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