

Evaluation of Farsite Simulator in a Mediterranean Area

Bachisio Arca ¹, Pierpaolo Duce ¹, Grazia Pellizzaro ¹,
Valentina Bacciu ², Michele Salis ², Donatella Spano ²

Abstract

Temporal and spatial variations of fire spread and behaviour can be predicted using one of the semi-physical or empirical models developed over recent years. The most common simulators (i.e., Behave and Farsite) are based on the Rothermel's original fire spread equation and describe fire spread as a function of relationships between fuels, terrain and weather conditions. The use of Farsite on areas different from those where the simulator was originally developed involves a local calibration to produce reliable results. The local calibration of Farsite requires the use of information provided by actual fires, and the choice of an appropriate standard or custom fuel model. The aim of this study was to analyse and compare the accuracy of Farsite simulations carried out in a Mediterranean area using different fuel models and meteorological input data. The study showed that a custom fuel model specifically designed for shrubland vegetation (maquis) provide more realistic values of rate of spread, when compared with predicted values obtained using standard fuel model. The use of both realistic wind field data and appropriate custom models seems to be essential to obtain reasonable simulations of fire behaviour on the different topographic and meteorological conditions that characterized the time steps of the actual fire. The study showed the capabilities of Farsite simulator during the typical drought season characterizing the Mediterranean climate, when most wild fires occur.

Introduction

The Mediterranean basin ecosystems are extremely sensitive and vulnerable due to the specific characteristics of the Mediterranean climate (climate variability, drought, etc.), and the large effects of different anthropogenic disturbances (modifications of land use, deforestation, grazing, forest fires, etc.). Fire is one of the most significant threats for the Mediterranean forested areas. In the last three decades, forest fires showed an increasing occurrence, with an annual average of about 50,000 forest fires, and a mean annual burned area of about 400,000 ha (EUR 22312 EN 2006, Schelhaas and others 2003). Statistical data also showed an increase in the number of extreme fire seasons. Therefore, the development of fire management policies are required in order to reduce the wildland fire risk by applying methods and models for planning the operational phases of fire management. Temporal and spatial variations of fire spread and behaviour can be predicted using one of the semi-physical or empirical models developed over recent years (Andrews, 2001, Perry, 1998). Farsite (Fire Area Simulator, Finney 1998) is

¹ Institute of Biometeorology, National Research Council, CNR-IBIMET, Via Funtana di Lu Colbu 4/A, 07100 Sassari, Italy. B.Arca@ibimet.cnr.it, P.Duce@ibimet.cnr.it, G.Pellizzaro@ibimet.cnr.it.

² Department of Economics and Woody Plant Ecosystems, University of Sassari, DESA, Via E. De Nicola 9, 07100 Sassari, Italy. vbacciu@uniss.it, miksalis@uniss.it, spano@uniss.it.

one of the main fire simulation systems. The simulator is based on the semi empirical fire prediction model developed by Rothermel (1972) and incorporated into the Behave Fire Behavior Prediction and Fuel Modeling System (Andrews, 1986). Since Farsite is a spatially and temporally explicit model, it can produce detailed analysis of fire behavior and fire effects (fire spread, fire-line intensity, burned area, etc.). To support these modeling 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 customized fuel models. Farsite was originally developed for long-range simulation of prescribed fires in US National forest, parks and wilderness areas. Therefore, the simulator was extensively validated using a large database of fires occurring in those areas. Several studies were followed to validating both the Rothermel's model and the Farsite simulator on areas different from those where the models were originally developed. Most of these studies were conducted in Europe and in Australia (van Wilgen and others 1985, Perry and others 1999, Sauvagnargues Lesage and others 2001, Dimitrakopoulos 2002, Miller and Yool, 2002, Bilgili and Saglam 2003, Pastor and others 2003, De Luis and others 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. The use of a simulator as component of a decision-support system for planning the fire management practices involves the assessment of the simulation accuracy under different environmental and vegetational conditions. The main aim of this study was to evaluate the capabilities of Farsite simulator in accurately forecasting the fire spread and behavior in a Mediterranean area predominantly covered by shrubland vegetation.

Materials and methods

Case studies

Farsite was used to simulate the propagation and behavior of a human-caused fire, which occurred in North Sardinia (Italy) during the 2004 summer season (*fig. 1*). The fire occurred near the village of Budoni, Italy, (lat. 40° 43', long. 09° 39', 50 m a.s.l.) in August 2004, in a hilly area where about 145 ha were burnt. The area is characterized by the typical sub-arid Mediterranean climate, with a remarkable water deficit from May through September, and most of the annual rainfall amount (approximately 650 mm) occurring in fall and winter. The mean annual temperature is approximately 17 °C, with summer season highs often around 30 °C. The average wind speed is relatively high ($\approx 4 \text{ m s}^{-1}$) in both winter and summer seasons, with about 50–70 percent of the days showing values between 1.6 and 8 m s^{-1} . The prevailing wind directions at the sites are typically west and northwest with a cumulative frequency greater than 50 percent. However, complex terrains typical of the studied areas can modify the local wind direction. The burned area (*fig. 1*) was mainly covered by the typical shrubland Mediterranean vegetation (approximately 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 about 22 ha and 19 ha, respectively. The fire started on August 26 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 about 36 km h⁻¹ in average. The fire was successfully extinguished by the Forest Service fire fighters only on the initial portion of the south flank, near the grassland area. On the opposite flank, near a ridgeline, the slope of terrain reduced the effect of the wind stopping the propagation of fire. The steep terrain and the strong upslope wind did not allow the 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 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. Cloud cover (CC) was estimated from solar radiation and extraterrestrial radiation. 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. In addition, wind speed and direction data were collected using a portable instrument (mod. MPM2000, Solomat Corp., Stamford, CT, USA) with the aim to perform further Farsite runs using wind maps in raster format and to determine the effect of wind field data on the accuracy of simulations. In particular, wind data were used 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 (1:10,000), field observation of the plant community and use of the 1:25,000 land cover map of Sardinia from the CORINE project (EEA ETC/TE 2002). Several simulations were run using three standard fuel models for shrubland vegetation and two for wooded pasture and grassland. Model n° 4 by Anderson (FM4), and models n° 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 types of Sardinia, covering about the 14 percent 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 (Fernandez 2001, Baeza and others 2002, Pellizzaro and others 2003, De Luis and others 2004, Pellizzaro and others 2005). The initial values of fuel moisture content (FMC) for the 10-h time lag (TL) dead fuel were determined calculating the relationship between observed FMC and fuel moisture sensor measurements (model CS505, Campbell Sci., Logan, UT, USA) 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 (Fernandez 2001, Baeza and others 2002, De Luis and others 2004). Grassland and open wooded pasture covers were assigned to the fuel models n° 1 (FM1) and n° 2 (FM2), respectively (Anderson 1982). In addition, the urban areas and roads were assigned to fuel model n° 91 (NB1, Scott and Burgan 2005). *Table 1* shows the main characteristics of each fuel model. Time step (20 minutes), 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 fire-fighting.

Statistical analysis

Several simulations were conducted to compare the performance of Farsite simulator when different combinations of fuel models and input parameters were used. 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. 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: the Cohen's kappa coefficient (Congalton and Green 1999, Congalton 1991) and the Sørensen coefficient (Legendre and Legendre 1998). Cohen's kappa coefficient (K) is a standard nonparametric measure of the classification accuracy, which allows evaluating the overall agreement between simulated and actual areas after random agreements by chance are removed. 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). The significance of the association was determined using the frequencies from the error matrix, and calculating the Chi-square 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 ($ROS = L/T, m \text{ min}^{-1}$). 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.

Table 1 – Input variables of standard and custom fuel models used to run the Farsite simulator on the Budoni case study (August 26, 2004). Standard fuel models include FM1, FM2, FM4, SH5 and SH7; CM28 is a custom fuel model designed and developed for maquis vegetation, and presented in this study.

Fuel mode code	FM1	FM2	FM4	SH5	SH7	CM28
Vegetation	Grass	Wooded pasture	Shrub	Shrub	Shrub	Shrub
- Dead Fuel Load (Mg ha ⁻¹)	1.66	7.84	24.70	12.78	24.66	9.86
1-hr	1.66	4.48	11.23	8.07	7.85	3.92
10-hr	0	2.24	8.99	4.71	11.88	3.92
100-hr	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-hr 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. (pct)	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

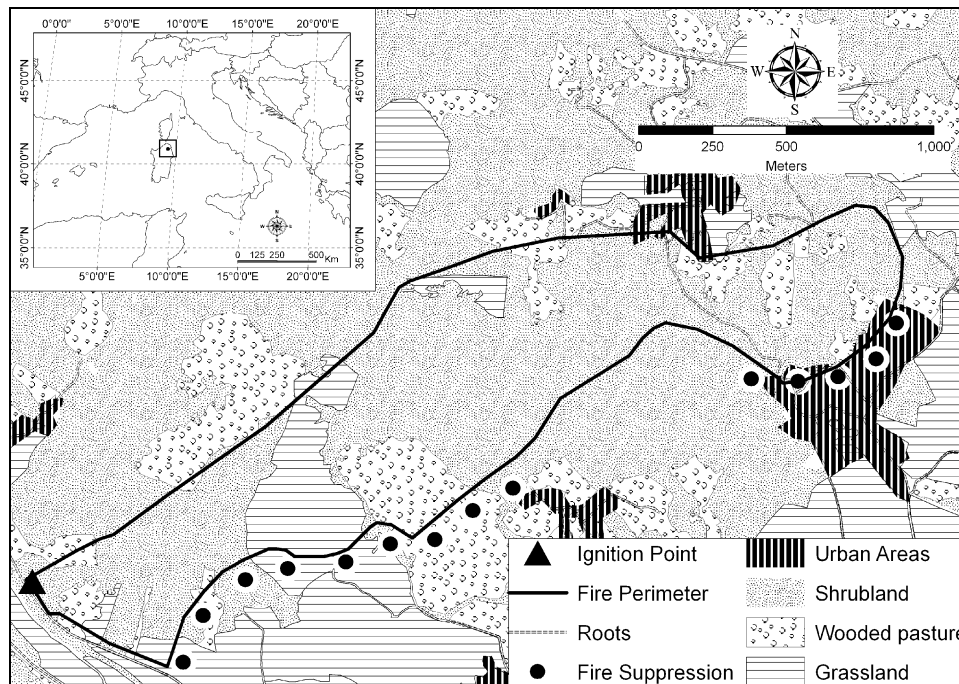


Figure 1 – Location of the human-caused fire event occurred during the 2004 drought season in North Sardinia, Italy (Budoni, August 26).

Results and Discussion

The values of the statistical parameters calculated by the different simulations are shown in *table 2*. 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 a p value ≤ 0.01 . The simulation n°4 provided the best value of K (0.61), whereas the other simulations (standard fuel models FM4, SH5, and SH7) gave K values ranging from 0.20 to 0.27. A comparison of the K values obtained from the different simulations was done using the Z test. Results showed that all the differences among simulations were significant at a p value ≤ 0.01 , confirming again that the best performance was given by the simulation n°4. Comparing the standard fuel models, the highest K value (0.27) was obtained using the SH7 model (simulation n°3). The bad performances (K = 0.20) of model FM4 (simulation n°1) can be attributed to the strong overestimation of the actual burned area. The Sørensen coefficient (SC) was used as an indicator of the exclusive association between the burned areas (actual and simulated). The SC values confirmed the above-mentioned results (*table 2*). Although all simulations gave significant values of association at a p value ≤ 0.01 using Chi-square test, the best agreement between observed and simulated burned areas was obtained using the simulation n°4 (SC = 0.72), while simulations n°1, 2 and 3 always showed values less than 0.52. FM4 and SH5 fuel models (simulations n°1 and 2, respectively) showed the lowest SC values. The rate of spread (ROS) gives general information on the combined effect of fuel and environmental conditions on fire behavior. Again, the best agreement between actual and simulated ROS was obtained by the simulation n. 4 (*table 2*). In general, the simulations performed using standard fuel models greatly overestimated the actual values of ROS. Since 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. Performances were evaluated calculating the SC values for three partial time steps (i.e., for three different burning periods): +2 hours, +3 hours and 30 minutes, and +6 hours and 30 minutes from the starting time. In addition, the effect on the simulation accuracy of the wind field data was evaluated (*table 3*). A good agreement between the actual and the simulated burned surface extensions was observed 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 percent), was confirmed during the second burning period, when a large burned surface was covered by grasslands (24 percent) and open wooded pastures (17 percent). 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 wind conditions. Simulations n°4 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, when a strong upslope wind propagated the fire. The simulation obtained using raster maps of wind 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 (*fig. 2*). Observed ROS (*table 4*) 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. 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 about 2.1 m min⁻¹ for the second burning period.

Table 2 – Statistical evaluation of Farsite simulator performance for different combinations of fuel models. 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.

Simulation / fuel model codes	K	SC	Observed ROS (m min ⁻¹)	Simulated ROS (m min ⁻¹)
1° (FM4, FM1, FM2)	0.20 ** A	0.47 **	8.1	22.3
2° (SH5, FM1, FM2)	0.23 ** B	0.49 **	8.1	20.7
3° (SH7, FM1, FM2)	0.27 ** C	0.52 **	8.1	16.7
4° (CM28, FM1, FM2)	0.61 ** D	0.72 **	8.1	08.1

** p-value ≤0.01; values of K followed by the same letters are not significantly different at a p-value ≤0.01 by Z-score test; SC values followed by ** indicate a significant association between burned and unburned areas at a p-value ≤0.01 by Chi-square test.

Table 3 – Values of the Sørensen coefficient (SC) from the simulation n° 4 (custom fuel model CM28) using raster maps and constant wind field. SC values for the whole surface area are also shown. All SC values showed a significant association between burned and unburned areas at a p-value ≤0.01 by Chi-square 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

Table 4 – Observed and estimated rate of spread (ROS m min⁻¹) from the simulation n° 4 (custom fuel model CM28). 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

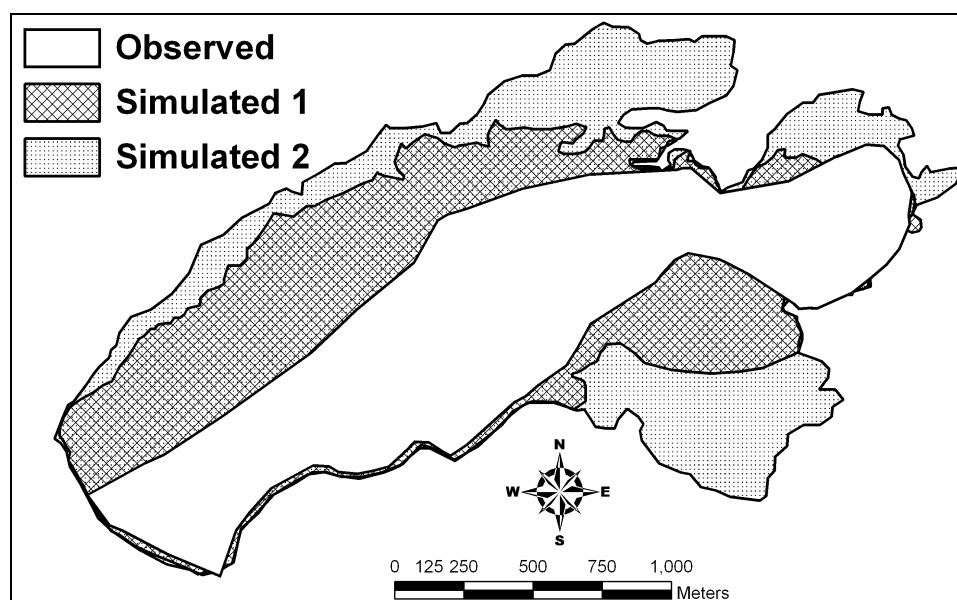


Figure 2 – Comparison between observed and simulated fire areas from the simulation n. 4 (custom fuel model CM28) using raster wind maps (Simulated 1) and constant wind field (Simulated 2).

Conclusions

In this paper, the performances of Farsite simulator in a Mediterranean area where shrubland vegetation is predominant were evaluated. The accuracy of Farsite was improved using a custom fuel model for maquis (CM28) designed and developed with the purpose of simulating fire spread and behavior on this type of vegetation. As reported by other authors (van Wilgen and others 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. A previous study by van Wilgen and others (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-hour), Dimitrakopoulos (2002) described the characteristics of two Mediterranean shrubland (maquis) fuel models, indicating that the 10 and 100-hour fuel load were significantly represented. In addition, Baeza and others (2002) showed the effect of plant age on the fuel load in large size classes. As reported by Sun and others (2006) for chaparral fuel, dead and live plant materials show differences in burning characteristics. In addition, the authors emphasized the importance of determining the effect of live chaparral on fire behavior. 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). Our results confirm that the performance of Farsite simulator is affected by the resolution and accuracy of wind data (Hanson and others, 2000). Improvements of the simulation accuracy could be obtained using high-resolution wind field data, calculated by computational fluid dynamics models (Kim and others 2000, Lopes and others 2002, Lopes 2003, Butler 2005). In conclusion, the use of both wind field data and appropriate custom fuel models is essential to obtain reasonable simulations of fire spread and behavior on Mediterranean vegetation during the drought season, when most of the annual wildfires occur. Information derived by databases of actual fires 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 analyze the effect of the limitations and assumptions of Rothermel's model on the simulation accuracy, and to evaluate the potential of Farsite simulator in planning the operational phases of fire management in Mediterranean Basin areas.

Acknowledgements

The authors would like to thank the personnel of the Sardinian Agrometeorological Service for providing weather data, and the Sardinian Forestry Corps (Cooperative agreement 27.12.2005) for providing GIS data and most of the information about the fire events. This work was partially funded by the Italian Ministry of Education, University and Scientific Research (MIUR), Grant N. 165 DM 1105/2002.

References

- Anderson H.E. 1982. **Aids to determining fuel models for estimating fire behaviour.** USDA For. Service General Technical Report INT-122. (Ogden, UT)
- Andrews P.L. 1986. **BEHAVE: fire behavior prediction and fuel modeling system-BURN subsystem, Part 1.** USDA Forest Service, Intermountain Research Station General Technical Report INT-194. (Ogden, UT)
- Andrews P.L., Queen L.P. 2001. **Fire modeling and information system technology.** International Journal of Wildland Fire 10: 343-352.
- Baeza M.J., De Luis M., Raventos J., Escarré A. 2002. **Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk.** Journal of Environmental Management 65: 199-208.
- Bilgili E., Saglam B. 2003. **Fire behavior in maquis fuels in Turkey.** Forest Ecology and Management 184: 201-207.
- Butler B.W. 2005. **Fire growth simulations of the Price Canyon, Thirtymile and Storm King Mountain fires using high resolution wind simulation tools and Farsite.** In Proceedings of 6th Symposium on Fire and Forest Meteorology; 2005, October 24-27, Canmore, AB, Canada.
- Congalton R.G. 1991. **A review of assessing the accuracy of classifications of remotely sensed data.** Remote Sensing of Environment 37: 35-46.
- Congalton R.G., Green K. 1999. **Assessing the Accuracy of Remotely Sensed Data: Principles and Practices.** New York: Lewis Publishers.
- Congalton R.G., Mead R.A. 1983. **A quantitative method to test for consistency and correctness in photointerpretation.** Photogrammetric Engineering & Remote Sensing 49(1): 69-74.
- De Luis M., Baeza M.J., Raventós J., González-Hidalgo J.C. 2004. **Fuel characteristics and fire behaviour in mature Mediterranean gorse shrublands.** International Journal of Wildland Fire 13: 79-87.
- Dimitrakopoulos A.P. 2002. **Mediterranean fuel models and potential fire behavior in Greece.** International Journal of Wildland Fire 11: 127-130.
- Dimitrakopoulos A.P., Papaioannou K.K. 2001. **Flammability Assessment of Mediterranean Forest Fuels.** Fire Technology 37: 143-152.
- EEA-ETC/TE 2002. **CORINE Land Cover update.** I&CLC2000, Technical Guidelines.
- EUR 22312 EN 2006. **Forest Fires in Europe 2005.** European Communities.
- Fernandes P.M. 2001. **Fire spread prediction in shrub fuels in Portugal.** Forest Ecology and Management 144: 67-74.
- Finney M.A. 1998. **Farsite: Fire Area Simulator-model development and evaluation.** USDA Forest Service, Rocky Mountain Research Station Research Paper RMRS RP 4. (Ogden, UT)
- Hanson H.P., Bradley M.M., Bossert J.E., Linn R.R., Younker L.W. 2000. **The potential and promise of physics-based wildfire simulation.** Env. Science & Policy 3: 161-172.
- Kim H.G., Patel V.C., Lee C.M. 2000. **Numerical simulation of wind flow over hilly terrain.** Journal of Wind Engineering and Industrial Aerodynamics 87: 45-60.
- Legendre P. and Legendre L. 1998. **Numerical Ecology.** Amsterdam: Elsevier.
- Lopes A.M.G. 2003. **WindStation – a software for the simulation of atmospheric flows over complex topography.** Environmental Modelling & Software 18: 81-96.

- Lopes A.M.G., Cruz M.G., Viegas D.X. 2002. **FireStation – an integrated software system for the numerical simulation of fire spread on complex topography.** Environmental Modelling & Software 17: 269-285.
- Ludwig J.A. and Reynolds J.F. 1988. **Statistical Ecology: a primer on methods and computing.** New York: John Wiley & Son; 339 pp.
- Miller J.D., Yool S.R. 2002. **Modeling fire in semi-desert grassland/oak woodland: the spatial implications.** Ecological Modelling 153: 229-245.
- Pastor E., Zárate L., Planas E. Arnaldos J. 2003. **Mathematical models and calculation systems for the study of wildland fire behaviour.** Progress in Energy and Combustion Science 29: 139-153.
- Pellizzaro G., Cesaraccio C., Asunis C., Caria C. 2003. **Analysis of fuel type and vegetation structure for fire risk index development.** In: Proceedings of the 2nd International Wildland Fire Ecology and Fire Management Congress, 2003, November 16-20, Orlando (FL).
- Pellizzaro G., Ventura A., Zara P. 2005. **Influence of seasonal weather variations on fuel status for some shrubs typical of Mediterranean Basin.** In: Proceedings of the 6th Fire and Forest Meteorology Symposium; 2005, October 25-27, Canmore, AB, Canada.
- Perry G.L.W., 1998. **Current approaches to modelling the spread of wildland fire: a review.** Progress in Physical Geography 22,2: 222-245.
- Perry G.L.W., Sparrow A.D., Owens J.F. 1999. **A GIS-supported model for the simulation of the spatial structure of wildland fire.** Cass Basin, New Zealand. Journal of Applied Ecology 36: 502-518.
- Pyne S.J. 1984. **Introduction to Wildland Fire.** New York: John Wiley & Sons; 455 pp.
- Richards G.D. 1990. **An elliptical growth model of forest fire fronts and its numerical solution.** International Journal for Numerical Methods in Engineering 30: 1163-1179
- Rothermel R.C. 1972. **A Mathematical model for predicting fire spread in wildland fuels.** USDA Forest Service Research Paper INT-115. Odgen, UT
- Sauvagnargues-Lesage S., Dusserre G., Robert F., Dray G., Pearson D.W. 2001. **Experimental validation in Mediterranean shrubs fuels of seven wildland fire rate of spread models.** Int. Journal of Wildland Fire 10: 15-22.
- Schelhaas M.J., Nabuurs G.J., Schuck A. (2003). Natural Disturbances in the European forests in the 19th and 20th centuries. Global Change Biology 9: 1620-1633.
- Scott J.H., Burgan R.E. 2005. **Standard fire behavior fuel models: a comprehensive set for use with Rothermels surface fire spread model.** Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 72 p.
- Sun L., Zhou X., Mahalingam S., Weise D.R. 2006. **Comparison of burning characteristics of live and dead chaparral fuels.** Combustion and Flame 144: 349-359.
- van Wilgen B.W., le Maitre D.C., Kruger F.J. 1985. **Fire modelling in South African fynbos (macchia) vegetation and predictions from Rothermels fire model.** Journal of Applied Ecology 22: 207-216.
- Watson D.F. and Philip G.M. 1985. **A refinement of Inverse Distance Weighted Interpolation.** Geoprocessing 2: 315-327.
- Wilson R. 1985. **Observation of Extinction and Marginal Burning States in Free Burning Porous Fuelbeds.** Combustion Science and Technology 44: 179-193.