CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF15081

Predicting wildfire spread and behaviour in Mediterranean landscapes

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Abstract. The use of spatially explicit fire spread models to assess fire propagation and behaviour has several applications for fire management and research. We used the FARSITE simulator to predict the spread of a set of wildfires that occurred along an east–west gradient of the Euro-Mediterranean countries. The main purpose of this work was to evaluate the overall accuracy of the simulator and to quantify the effects of standard vs custom fuel models on fire simulation performance. We also analysed the effects of different fuel models and slope classes on the accuracy of FARSITE predictions. To run the simulations, several input layers describing each study area were acquired, and their effect on simulation outputs was analysed. Site-specific fuel models and canopy inputs were derived either from existing vegetation information and field sampling or through remote-sensing data. The custom fuel models produced an increase in simulation accuracy, and results were nearly unequivocal for all the case studies examined. We suggest that spatially explicit fire spread simulators and custom fuel models specifically developed for the heterogeneous landscapes of Mediterranean ecosystems can help improve fire hazard mapping and optimise fuel management practices across the Euro-Mediterranean region.

Additional keywords: ecosystems, fire management, fuel, modelling, propagation.

Received 7 April 2015, accepted 10 June 2016, published online 2 August 2016

Introduction

Southern European countries account for as much as 75% of the fires and nearly 90% of the total burned area of the whole of Europe (Schmuck *et al.* 2011): in this area, since 1980 ∼50 000 fires per year have been recorded, burning ∼465 000 ha of wildland (Schmuck *et al.* 2011). In the Mediterranean basin, several studies have reported the relationships among wildfire events, fire weather and fuels (Moreno *et al.* 2011; Koutsias *et al.* 2012; Duguy *et al.* 2013; Ganteaume and Jappiot 2013; Xystrakis and Koutsias 2013; Ager *et al.* 2014*a*). Many studies have explained a substantial part of the intense wildfire activity with the extensive land abandonment observed since 1970

(Pausas and Vallejo 1999; Duguy and Vallejo 2008; Moreira *et al.* 2011; Pausas and Fernández-Muñoz 2012; Viedma *et al.* 2015). In Mediterranean landscapes, the occurrence of large fires is mainly attributed to the presence of severe and extreme meteorological conditions (strong wind, heat weaves, etc.) and the manner in which fire propagates (i.e. crown fires, spotting) compared with smaller fire events (Pereira *et al.* 2005; Viegas *et al.* 2009; Dimitrakopoulos *et al.* 2011). As wildfires are increasingly affecting human and ecological resources, interest in developing new wildfire risk assessment methodologies and tools based on fire behaviour modelling has risen in recent years (Miller and Ager 2013).

Wildland fire behaviour modelling has its origin back in the early 20th century and encompasses a range of various mathematical approaches, which assemble a collection of equations for the estimation and prediction of fire spread and behaviour at different spatiotemporal extents and settings (Pastor *et al.* 2003). Though fire models can be described according to different factors (nature of the equations, variables included, physical system modelled, etc.), they are commonly classified into three broad categories: (i) physical and quasi-physical models; (ii) empirical and quasi-empirical models; and (iii) simulation and mathematical analogue models (Sullivan 2009*a*; Sullivan 2009*b*). Each of these categories has some advantages and disadvantages, depending on the computational effort, accuracy, transferability, robustness, data demands and costs. Yet, in recent years, significant efforts have been concentrated on developing numerical simulation techniques to allow the expansion of existing one-dimensional linear models to two- or three-dimensional models of fire spread across the landscape (Finney 1998, 2002; Linn *et al.* 2002; Linn *et al.* 2007; Sullivan 2009*b*). The capability of different fire spread models and simulators to support fire management in Mediterranean Europe has been investigated by several authors (Arca *et al.* 2007*a*, 2007*b*; Duguy *et al.* 2007; Carmel *et al.* 2009; Filippi *et al.* 2010; Papadopoulos and Pavlidou 2011; Paz *et al.* 2011; Santoni *et al.* 2011; Hollingsworth *et al.* 2012; Salis *et al.* 2013, 2014, 2015, 2016; Alcasena *et al.* 2015, 2016; Kalabokidis *et al.* 2015; Mitsopoulos *et al.* 2015). Among the various approaches, the FARSITE fire area simulator (Finney 1998) is probably the most widely used fire simulation system for single fire events, as it is able to perform spatially and temporally explicit simulations of fire spread and behaviour, is user-friendly and is freely available. This simulator extends the capabilities of point-based models such as the BEHAVE Fire Behaviour Prediction and Fuel Modelling System (Andrews 1986), originally developed from the semi-empirical surface fire spread model of Rothermel (1972), to calculate fire propagation and behaviour in two dimensions or across a landscape. The description of the simulator equations as well as the limitations and assumptions of the modelling methods used in FARSITE are reported in several works (Finney 1998; Stratton 2006).

In a landscape, as there are numerous potential combinations of vegetation types, characteristics and succession stages, and it is almost impossible to characterise all possible combinations, the most common approach used for fire-spread modelling is to generalise and characterise fuels into a finite number of fuel models (Keane *et al.* 2001; Cai *et al.* 2014). A fuel model is an identifiable association of forest fuel components of distinctive species, form, size, arrangement and continuity that will exhibit characteristic fire behaviour under defined burning conditions (Anderson 1982). In recent years, much effort has been dedicated to developing an alternative to standard fuel models (Deeming *et al.* 1972; Anderson 1982; Scott and Burgan 2005). In fact, although FARSITE provides reliable results in fire behaviour modelling over landscapes containing fuel types consistent with the original standard fuel models of Anderson (1982) and Scott and Burgan (2005) designed for US fuel types, extrapolation to other ecosystems is not always an easy and reliable task and can result in biased outputs (Pastor *et al.* 2003; Arca *et al.* 2007*b*; Arroyo *et al.* 2008; Jahdi *et al.* 2015, 2016). Several customised fuel models have been recently developed to better represent the fuel characteristics of the Mediterranean vegetation in Greece (Dimitrakopoulos 2002), the medium-height (maquis) and low and degraded shrublands (garrigue) communities in Italy (Arca *et al.* 2007*b*, 2009), the shrub vegetation in Turkey (Bilgili and Saglam 2003; Sağlam *et al.* 2008), *Pinus pinaster* stands in Portugal (Fernandes 2001; Cruz and Fernandes 2008), and the grass, shrub and canopy fuel types in Spain (De Luis *et al.* 2004; Rodríguez y Silva and Molina-Martínez 2012; Vega-Garcia *et al.* 2014). Previous studies conducted using fire behaviour modelling suggested that site-specific fuel data could increase the accuracy of predicted fire behaviour over standard fuel models (Miller and Yool 2002; Arca *et al.* 2007*b*; Cheyette *et al.* 2008; Mutlu *et al.* 2008; Salis 2008; Cai *et al.* 2014). Yet only few works have tested the robustness and accuracy of the fire simulation process with actual recent fires that occurred in the Mediterranean Basin (Arca *et al.* 2007*b*; Paz *et al.* 2011; Salis *et al.* 2013).

Fire spread and behaviour are also affected by topography, because fires spread more quickly upslope and more slowly downslope; nevertheless, terrain has a significant influence on wind flows. Overall, fire spread models based on Rothermel's equation (Rothermel 1972) are not able to capture the coupled effects of topography and wind on fire propagation and behaviour in complex areas (Weise and Biging 1997; Santoni *et al.* 1999; Finney 1998; Viegas 2004; Viegas and Pita 2004). To address the wind–terrain limitations for several fire spread models, the use of mass-consistent wind models can allow for wind flow as a spatially and temporally variable input across a study area or allow the determination of preferential local wind patterns based on local conditions (Carvalho *et al.* 1997; Werth *et al.* 2011; Forthofer *et al.* 2014*a*, 2014*b*).

The validation of spatially explicit fire behaviour simulations is a complex task, and most fire behaviour studies do not provide any statistical estimate of the agreement between modelled and observed fire perimeters and behaviour, mainly owing to the difficulty of accurately describing the observed fires (Fujioka 2002; Paz *et al.* 2011; Jahdi *et al.* 2016). Nevertheless, to incorporate fire spread simulation in operational workflows, it is crucial to increase the model accuracy by suitable validation. The validation of modelled fire behaviour results allows a timely calibration before a fire event or incident, thus increasing the potential for applicability (Hollingsworth *et al.* 2012).

In the present work, we used the FARSITE simulator to predict the spread and behaviour of a set of wildfires that occurred along an east–west gradient of the Euro-Mediterranean countries. The main purpose of this study was to evaluate the overall accuracy of the simulated fire perimeters in complex and heterogeneous Mediterranean landscapes and to compare the accuracy of the simulations performed with standard and customised fuel models. Then, we analysed the effects of fuel models and slope classes on both fire spread and behaviour indicators as well as on simulation accuracy.

Materials and methods

Description of the case studies

The case studies cover a wide gradient of different weather conditions, topography, vegetation types and fire size across the Mediterranean Basin (Table 1 and 2, Figs 1 and 2, and online supplementary material). The selected wildfires occurred between 1990 and 2011 and affected some of the most fire-prone European areas. Four case studies were located in Sardinia, Italy (Lochiri, Nuoro, Monte Doglia and Budoni), three in Greece (Alexandroupoli, Attica and Penteli), and five in Spain (Vall de Gallinera, Collado, Fresnedoso de Ibor, Hurdes and Navalmoral) (Table 1 and Fig. 1). We analysed wildfires of different size, including: two very large fires that burned more than 7000 ha (Nuoro and Attica); three large fires, ranging from 1000 to 4000 ha (Penteli, Hurdes and Lochiri); and seven medium–large fires that burned between 70 and 600 ha (Table 1). For all the case studies, fire duration was considered as the temporal interval between fire ignition and the end of active fire suppression activities, without taking into account mop-up operations, and fire size reflected the perimeter burned in this interval. The majority of the fires analysed lasted less than 24 h. The Hurdes wildfire was the only one that spread actively for almost 5 days. With the exception of Monte Doglia, which took place at the end of May, the case study fires were ignited in July or August, which is the peak fire season in the Mediterranean Basin (Table 1). Overall, the fires mostly affected Mediterranean shrublands, but herbaceous and wooded pastures were also burned in several cases (Table 1 and Table S2 in the online supplementary material). Though the main vegetation types were similar, each study area revealed specific fuel characteristics in terms of fuel load and depth, surface area-to-volume (SAV) ratio, and other variables as specified in Table S3). The information and data on the actual fires investigated in this study were provided by the local fire managers and Forest Services.

Fire spread and behaviour simulations

Fire simulations were performed using the FARSITE simulator (Finney 1998) in order to obtain spatial and temporal simulations of fire spread and behaviour for each case study. The required geospatial input layers describing the landscape were processed, analysed and assembled into the landscape file (LCP) within a Geographic Information Systems (GIS) environment (ArcMap 10; ArcFuels 10, Ager *et al.* 2011). All the information and data related to fire perimeters and spread were provided by the local fire managers. We set the resolution of the landscape layers at 50 m for the very large fires (Nuoro and Attica), at 25 m

Table 2. Interpretation of kappa (KC) and Sorensen (SC) coefficients values, adapted from Filippi *et al.* (2014)

KC and SC value range	Interpretation
<0	No agreement
]0.0–0.2]	Slight agreement
]0.2–0.4]	Fair agreement
]0.4–0.6]	Moderate agreement
]0.6–0.8]	Substantial agreement
]0.8–1.0]	Almost perfect agreement

Table 1. Summary of the case studies analysed
Med., Mediterranean

Case study	Country	Fire size (ha)	Date of ignition	Active fire spread duration (h)	Average area burned per hour (ha h^{-1})	Main vegetation types	Elevation (m above sea level)
Alexandroupoli	Greece	124	23 August 2011	6	21	Wooded areas, Med. maquis	30–335
Attica	Greece	7040	21 August 2009	16	925	Pastures, wooded pastures, Med. maquis, pines	0–1095
Budoni	Italy	141	26 August 2004	5	29	Wooded pastures, Med. maquis	5–335
Collado	Spain	373	18 July 2011	13	29	Wooded pastures, Med. maquis	240–485
Fresnedoso de Ibor	Spain	201	17 July 2011	7	29	Olive grove, Med. maquis, pastures	410–795
Hurdes	Spain	3092	25 July 2011	115	27	Med. forest, Med. maquis, pastures	375–1465
Lochiri	Italy	2520	13 July 2011	6.5	385	Pastures, wooded pastures	150–890
Monte Doglia	Italy	70	30 May 2006	2	34	Med. maquis	45–410
Navalmoral	Spain	86	28 July 2011	2	43	Pastures, Med. maquis	340–445
Nuoro	Italy	7460	23 July 2007	10	740	Pastures, wooded pastures, Med. maquis	45–1350
Penteli	Greece	3720	21 August 2009	24	140	Shrublands, grasslands, Aleppo pine forests	0–1095
Vall de Gallinera	Spain	591	24 July 1990	24	46	Pastures, shrublands	85–810

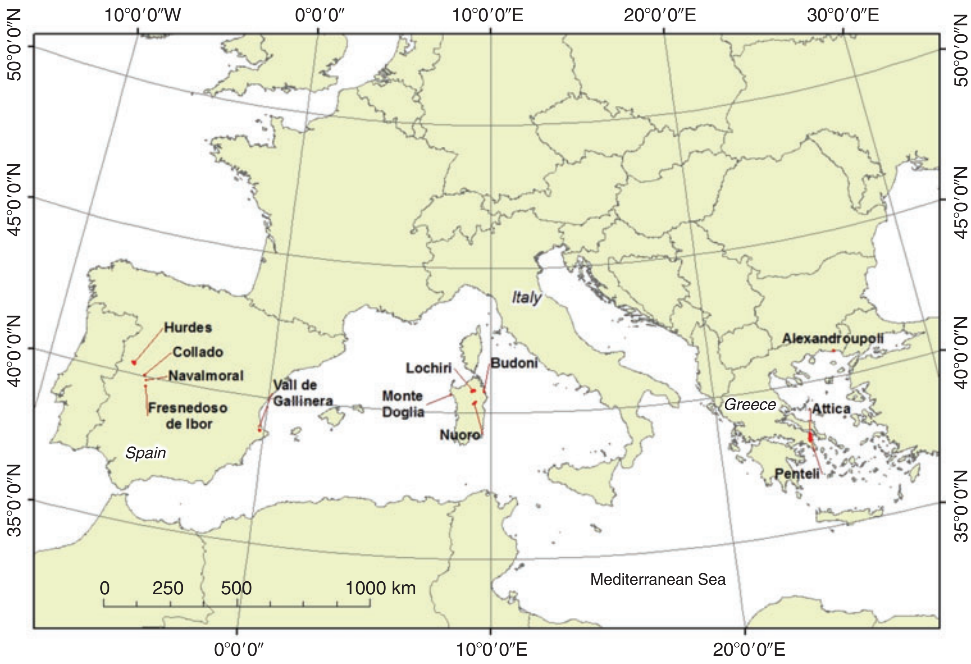

Fig. 1. Location of the case studies analysed.

for the large fires (Penteli, Hurdes and Lochiri), and at 10 m for the medium–large-size case studies (the remaining seven case studies). These resolutions were considered sufficiently accurate to ensure reliable and realistic wildfire simulations, especially considering the spatial resolution of the input themes used to feed the simulator.

Terrain data (elevation, slope and aspect) were derived from digital elevation models (DEM), whereas surface fuel and canopy cover maps were derived either from existing vegetation and land-use maps (e.g. Corine Land Cover, EEA 2002) or from site-specific mapping based on aerial photographs or satellite imagery (e.g. http://earthexplorer.usgs.gov, accessed 29 June 2016). The standard surface fuel models used for the simulations were those developed by Anderson (1982) and Scott and Burgan (2005). The selection of the standard fuel models for the simulations was based on the similarity to actual fuels in terms of general fire-carrying fuel type, fuel properties (e.g. depth, live fuel load, compactness), photo-guides and expected fire behaviour. A set of custom fuel models (see Table S3 and Fig S1) was also developed by using field data collected for most case studies.

For each case study, we performed a set of preliminary FARSITE simulations using different standard fuel models, as well as customised fuel models. In the present work, we only describe the results obtained by the most accurate simulations (as measured by Kappa and Sorensen indices) obtained using specific combinations of standard and customised fuel models for each case study. The standard and custom fuel model codes, as well as the custom fuel data used as input for the FARSITE simulations presented in this work, are reported in Tables S2 and S3. Further, the canopy fuel information required to model crown fires, including stand height (m), crown base height (m) and crown bulk density (kg m^{-3}), were provided by the national forest inventory systems (e.g. Italy, INFC 2005; Spain, Ministerio de Agricultura 2007), derived from field sampling or estimated by regression equations based on forest stand parameters (Mitsopoulos and Dimitrakopoulos 2014). The initial values of fuel moisture content as well as the other fuel variables (SAV ratio, heat content, moisture of extinction, etc.) were determined for each case study considering the values of the standard fuel models and the most relevant studies conducted in Mediterranean areas (Dimitrakopoulos 2001; Dimitrakopoulos and Panov 2001; Arca *et al.* 2007*b*, 2009; Duguy *et al.* 2007; Pellizzaro *et al.* 2007; Salis *et al.* 2015). When available, fuel data collected during specific sampling campaigns were also used. In more detail, fuel moisture values for live and dead fuels were set empirically based on field sampling, mostly performed some days after the wildfire event. The moisture values of the fine dead fuel ($<$0.6 cm in diameter), expressed as percentage of dry weight, ranged between 3 and 35%, and were below 10% for most of the fires studied. The moisture values of the live woody components ranged between 70 and 130%, with the lowest values observed in the shrubland fuel types of Sardinia. Herbaceous fuels were considered fully cured, with the exception of irrigated areas (e.g. Vall de Gallinera).

The wind data observed in the closest weather stations to each wildfire, as well as the elevation data and the dominant vegetation of the modelling areas, were provided as inputs to the mass-consistent model WindNinja (Forthofer 2007; Forthofer and Butler 2007; Forthofer *et al.* 2014*a*, 2014*b*) to generate raster grids of wind speed and direction (on an hourly basis and at 2-m height) for use in FARSITE simulations.

Concerning the FARSITE simulation parameters, we set the resolution of perimeter and distance calculations in the range 10–50 m, and fire spread isochrone projections from 10 to 30 min, depending on the size of the study area, to ensure a satisfactory resolution level for the projections of fire perimeters.

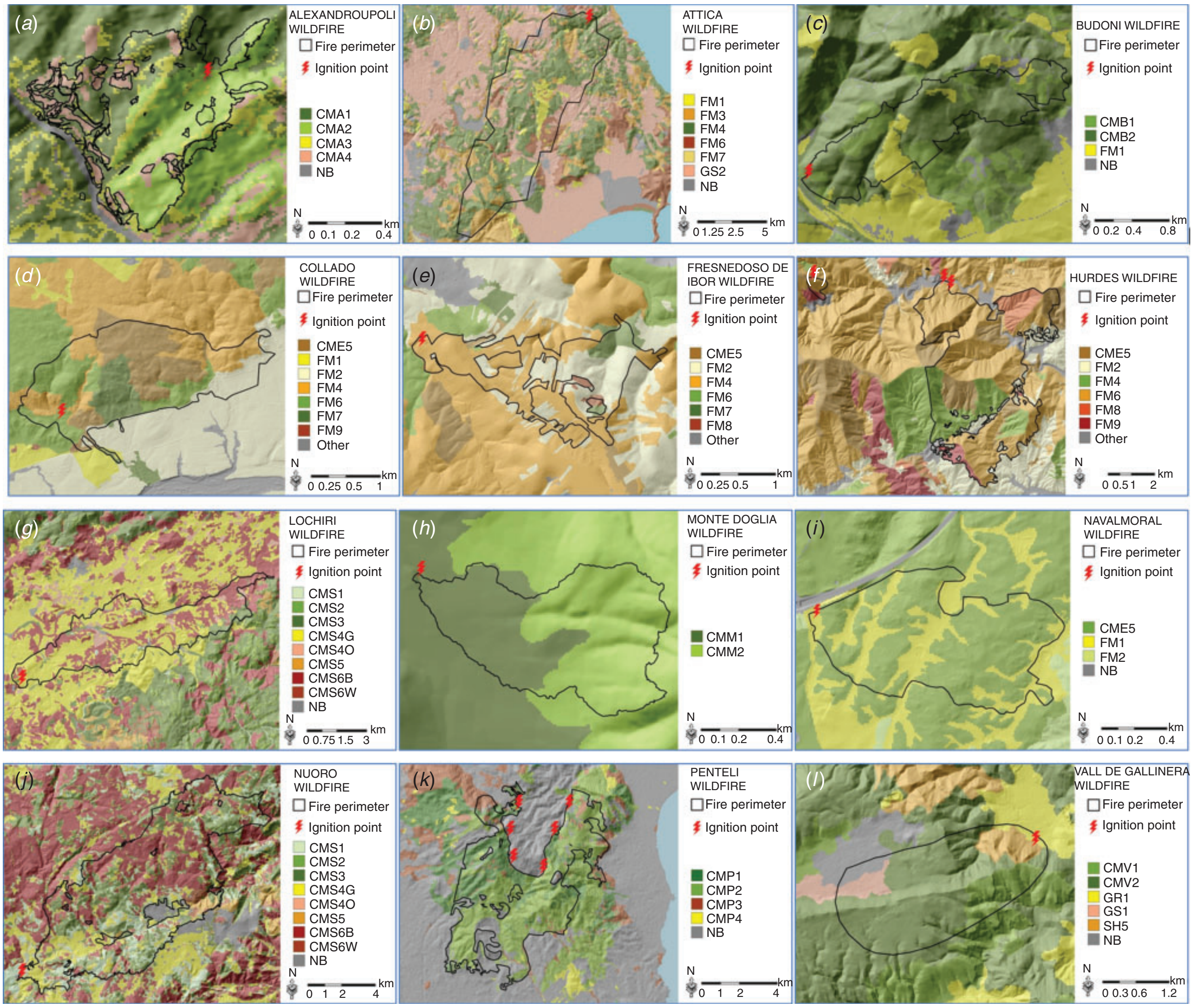

Fig. 2. Maps of the actual fire perimeters, ignition point locations and fuel models: (*a*) Alexandroupoli; (*b*) Attica; (*c*) Budoni; (*d*) Collado; (*e*) Fresnedoso de Ibor; (*f*) Hurdes; (*g*) Lochiri; (*h*) Monte Doglia; (*i*) Navalmoral; (*j*) Nuoro; (*k*) Penteli; and (*l*) Val de Gallinera. The data on fire perimeters and ignition points were provided by the local fire management agencies. The fuel model codes are defined in Table 4.

The local fire managers reported spot fire phenomena for five case studies (Lochiri, Nuoro, Attica, Hurdes and Vall de Gallinera): spot fires were simulated from torching trees for passive and active crown fire as implemented in the FARSITE simulator (Albini 1979). Based on the interviews and data gathered from the various Forest Services, the spot fire ignition frequency was set between 1% (Hurdes) and 5% (Vall de Gallinera), while the spot fire ignition delay was in the range between 0 and 2 min after firebrands landing. For the case studies of central Spain, a set of barriers was defined using FARSITE functionalities in order to consider the terrestrial and aerial attacks that were reported as effective in stopping wildfire spread. The decision of using barriers only for these case studies was related to the availability of accurate information and localisation of the areas where suppression activities were able to efficiently block the fire spread. For the other case studies, either this information was absent or inaccurate, or the suppression activities were not able to block fire propagation.

We gathered a set of FARSITE outputs, which were (1) the contours of the simulated partial and final fire perimeters, and (2) the grid files of the simulated fire behaviour corresponding to time of arrival (h), rate of spread (m min^{-1}), rate of size growth (ha h^{-1}) and flame length (m).

Assessment of the accuracy of simulations

We assessed the accuracy of fire perimeters of the FARSITE simulations performed with standard and custom fuel models in each study area. Additionally, the performance of the most accurate simulation for each case study was analysed across the different fuel models, as well as within different slope ranges. For this purpose, we first calculated an error matrix between actual and simulated burned areas to define the frequency of each case (presence or absence of burned areas) (Fig. 3). Then,

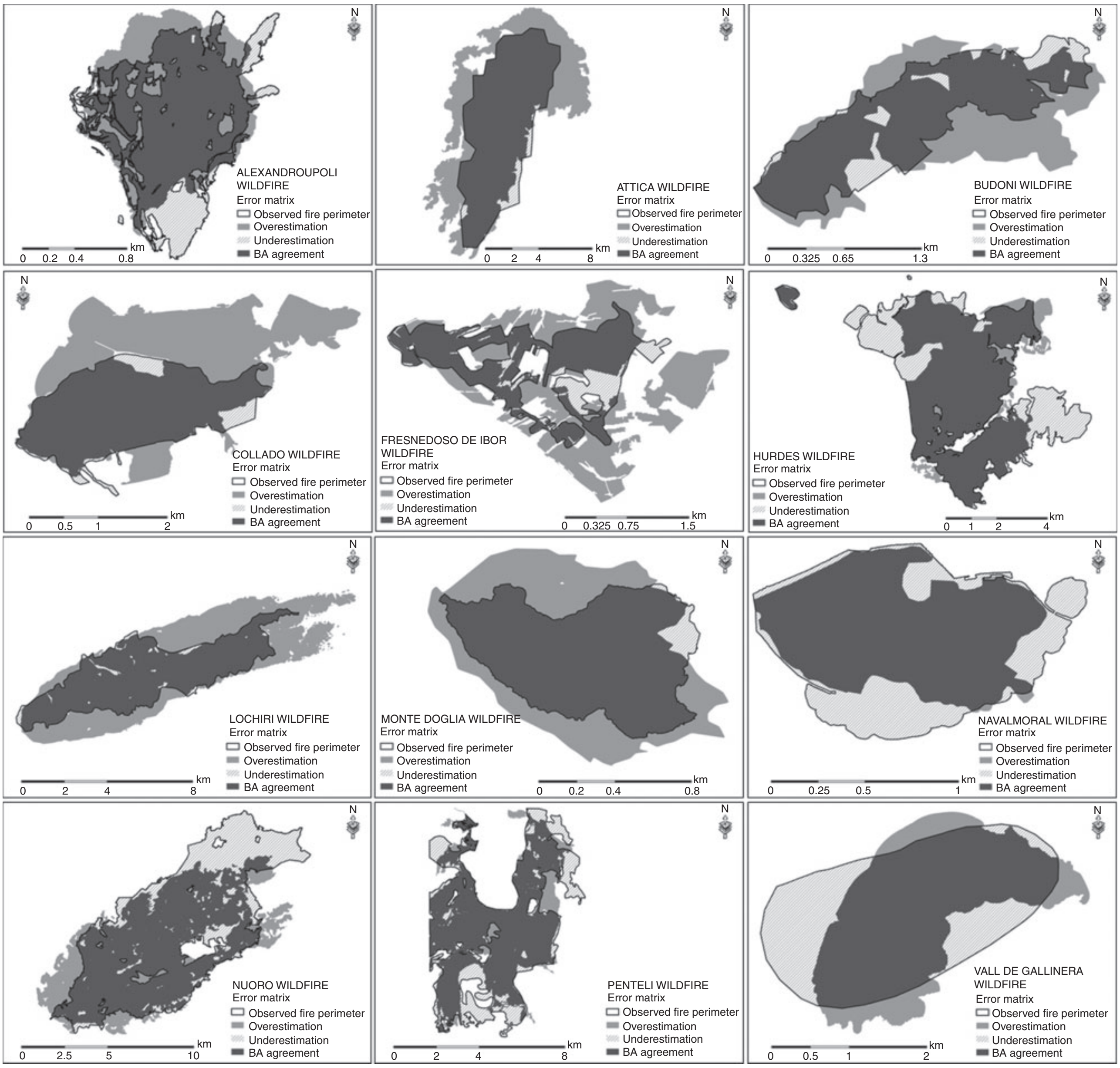

Fig. 3. Maps of overestimation, underestimation and agreement between simulated and observed fire perimeters for each of the case studies analysed. The results refer to the simulations performed using the custom fuel models. BA, Burned Area.

we used two statistical indicators of accuracy derived from the error matrix: Cohen's kappa coefficient (KC, Congalton 1991), and the Sorensen coefficient (SC, Sorensen 1948).

KC is a non-parametric measure of classification accuracy that allows evaluation of the overall agreement between simulated and actual burned areas after chance agreements are removed. KC is given by:

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

where r is the number of rows in the error matrix, N is the total number of observations, x_{ii} is the number of observations in row i and column i, and x_{i+} and x_{+i} are the marginal totals of row i and column i respectively. KC values range between zero and one, with perfect agreement when KC equals 1 (Table 3). The significance of the coefficient KC was evaluated with the Z-test, in order to assess if the classification derived from the error matrix was significantly better than chance agreement (Salis 2008). The non-parametric test of McNemar (Agresti 1996; Foody 2004), based on the chi-square distribution, was then used for evaluating the significance of the difference in KC between custom and standard fuel model simulations (Table 3).

SC is an asymmetric statistical index derived from the error matrix and computes the portion of similarity between two

Table 3. Analysis of the FARSITE outputs obtained using custom fuel models vs standard fuel models

KC, kappa coefficient; SC, Sorensen coefficient; OI, overestimation index; Obs., observed; Sim., simulated; avg., average; ROS, rate of spread; FL, flame length. Values of KC followed by ** indicate significant accuracy with respect to chance agreement at $P \leq 0.01$. Comparison between custom and standard fuel model simulations: values of McNemar chi-square followed by ** indicate significant differences at $P \leq 0.01$; values of McNemar chi-square followed by * indicate significant differences at $P \leq 0.05$

Case study	Fuel models	KC	Chi-square McNemar	SC	OI	Obs. fire size (ha)	Sim. fire size (ha)	Obs. avg. size growth (ha h^{-1})	Sim. avg. size growth (ha h^{-1})	Sim. avg. ROS in the fire front (m min^{-1})	Sim. max ROS (m min^{-1})	Sim. avg. FL (m)	Sim. max FL (m)
Alexandroupoli	Custom	0.70**	528.12**	0.75	0.25	124	144	21	24	3.3	17.3	2.4	19.0
	Standard	0.36**		0.49	1.00		381		64	6.3	23.9	1.9	12.5
Attica	Custom	0.60**	207.52**	0.74	0.89	7040	10957	440	685	18.9	64.0	4.4	24.0
	Standard	0.29**		0.46	1.00		23057		1441	16.2	66.0	4.8	26.0
Budoni	Custom	0.59**	4333.03**	0.65	0.78	141	229	28	46	10.0	64.7	2.6	10.5
	Standard	0.40**		0.43	−1.00		36		7	9.3	49.3	2.1	7.3
Collado	Custom	0.54**	0.03	0.61	0.86	373	713	29	55	6.2	38.0	9.0	18.0
	Standard	0.58**		0.65	0.67		630		48	6.5	45.0	10.0	21.0
Fresnedoso de Ibor	Custom	0.53**	3140.41**	0.56	0.67	201	365	29	52	21.4	105.0	20.0	40.0
	Standard	0.49**		0.52	0.85		449		64	21.0	103.0	19.0	39.0
Hurdes	Custom	0.78**	3866.98**	0.82	0.60	3092	3729	27	32	1.8	59.0	14.0	28.0
	Standard	0.75**		0.79	0.71		4200		37	1.5	49.0	12.0	23.0
Lochiri	Custom	0.62**	4424.46**	0.68	0.75	2520	4764	388	733	41.0	39.7	5.0	45.0
	Standard	0.37**		0.50	0.75		5729		881	61.9	114.5	3.9	41.5
Monte Doglia	Custom	0.70**	312.00**	0.73	1.00	70	111	35	56	11.5	35.6	2.9	7.5
	Standard	0.37**		0.44	1.00		251		126	22.1	82.3	3.2	8.1
Navalmoral	Custom	0.80**	5.55*	0.82	1.00	86	108	43	54	12.3	48.0	11.0	22.0
	Standard	0.77**		0.80	1.00		116		58	12.3	48.0	11.0	22.0
Nuoro	Custom	0.76**	397.67**	0.80	−0.14	7460	7122	746	751	20.6	46.0	5.5	27.5
	Standard	0.61**		0.67	0.11		7507		712	31.6	99.1	2.4	24.5
Penteli	Custom	0.72**	5899.85**	0.81	−0.47	3720	3209	155	134	4.6	111.0	4.6	33.0
	Standard	0.53**		0.72	0.44		4917		205	5.1	115.7	3.2	27.1
Vall de Gallinera	Custom	0.74**	1419.00**	0.75	0.00	591	517	25	22	2.7	4.0	1.8	5.0
	Standard	0.38**		0.42	1.00		1902		79	3.6	6.0	1.5	4.0

samples. It indicates the exclusive association between the two areas burned (observed and simulated), and is calculated as:

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

where a is the number of cells coded as burned in both observed and simulated data, b is the number of cells burned overestimated by the simulation, and c is the number of cells burned underestimated by the simulation. SC ranges between 0 and 1, with values closest to one indicating the highest agreement, whereas 0 means no agreement (Table 3).

KC is frequently used to perform accuracy assessment and evaluate land-use or other spatial classifications. Yet it is influenced by landscape size, as it varies with the dimension of the study area. For this reason, when preparing the landscape file for each case study, we established that the burned-area category should range between 15 and 25% of the whole study area, so that the unburned areas agreement affected the results in a similar way in all case studies. Moreover, we delimited the study areas taking care that the simulated wildfires did not spread beyond the landscape boundaries. Therefore, the SC and KC metrics were independent of the landscape size and SC contributed to strengthening the simulation accuracy assessment.

In order to analyse the main source of error (overestimation or underestimation) of FARSITE simulations, starting from the error matrix, we derived an overestimation index (OI), which was calculated as follows:

$$OI = \frac{(b - c)}{(b + c)}$$

This index ranges between 1 and -1, with the highest values associated with major errors of overestimation, and the lowest with underestimation. OI values close to 0 indicate limited differences among overestimated and underestimated cells.

Data about partial fire perimeters, rate of spread (ROS) and flame length (FL) observed during the actual fires were obtained from fire reports, pictures collected during the events and interviews. These data only permitted localised comparisons with the simulated values. The comparison between observed and simulated fire spread was performed considering the average rate of fire area growth. Further, the average rate of spread in the fire front, the maximum ROS (m min^{-1}) and average and maximum FL (m) were computed for all case studies based on FARSITE outputs.

Results

All simulations estimated the spatial extension of burned areas better than random chance ($P = 0.01$, Table 3). In almost all case studies, the use of custom fuel models improved the performance of FARSITE in predicting fire spread when compared with standard fuel models (Table 3, Fig. 3). In particular, the wildfire simulations performed using custom fuel models resulted in a significant increase in fire area accuracy (McNemar chi-square, $P = 0.01$) when compared with standard fuel models, with the exception of the case studies of Collado and Navalmoral, where no significant statistical differences and significant differences only at $P = 0.05$ were observed respectively (Table 3). The largest improvements in the accuracy (30–36% in terms of KC, 26–33% in terms of SC) of the simulated fire areas when using custom fuel models instead of standard ones were observed for the case studies of Alexandroupoli, Attica, Monte Doglia and Vall de Gallinera (Table 3). In the case studies where the custom models covered only small areas compared with the whole area burned (Hurdes, Collado, Navalmoral and Fresnedoso de Ibor), the difference in both KC and SC between custom and standard fuel model simulations was limited to 2–5% (Table 3). In the remaining case studies, the custom models led to less pronounced improvements of accuracy (15–25% in terms of KC, 9–22% in terms of SC) (Table 3).

In most cases, the use of standard fuel models resulted in a larger overestimation of the burned areas (e.g. simulations with standard fuel models: OI = 1 in five case studies; simulations with custom fuel models: OI = 1 in two case studies), with the exception of the Budoni fire, where the use of standard fuel models caused a large underestimation of the area burned and OI equalled -1 (Table 3). The simulations with standard and custom fuel models resulted in similar OI values in the case studies of Lochiri and Hurdes. Moreover, the custom fuel models provided an underestimation only in the case studies of Penteli (OI = -0.47) and Nuoro (OI = -0.14) (Table 3). In Monte Doglia, Vall de Gallinera, Attica and Alexandroupoli, the final size and growth rates of the simulated fires using the standard fuel models were more than double compared with the custom models. Only for three case studies (Nuoro, Budoni and Collado), the standard models produced fire growth rates and final sizes smaller than those obtained using custom models.

As mentioned above, custom fuel models used in FARSITE simulations gave better results compared with standard fuel models, with substantially better agreement with the observed fire area in most of the case studies (11 out of 12) as indicated by the SC and KC indices (Tables 2 and 3; Fig. 3). For this reason, in order to describe the effects of fuel models and slope classes on fire spread and behaviour, the results obtained using only custom fuel models are presented hereafter (Tables 4 and 5).

The average ROS of the simulated fire front showed different mean values depending on the case study (Table 4, Fig. 4). The highest average ROS, ~40 m min^{-1}, was estimated for the Lochiri fire. Other fire events (Fresnedoso de Ibor, Nuoro and Attica) presented average values of ~20 m min^{-1}, whereas lower ROS values were obtained for the other case studies. Very high values of maximum ROS (even exceeding 100 m min^{-1}) were simulated in areas with very steep terrain covered by large amounts of fine fuels (e.g. grasslands) and shrublands, for example in the fire events of Penteli and Fresnedoso de Ibor. For all the other case studies, the maximum ROS values varied between 40 and 65 m min^{-1}, with the exception of Vall de Gallinera, where the maximum ROS was 4 m min^{-1}.

The average FL values (Table 4, Fig. 4) were higher than 10 m for the Spanish case studies of Collado, Navalmoral, Fresnedoso de Ibor and Hurdes: this was related to the use of barriers for the simulations of these events, to account for firefighting intervention. The barriers were located in areas where firefighting intervention was reported as safe and effective in stopping fire spread, and in low–moderate fire intensity

Table 4. Effect of the main fuel models in simulation accuracy and fire behaviour, considering the simulations performed using the custom fuel models

KC, kappa coefficient; SC, Sorensen coefficient; OI, overestimation index; Obs., observed; Sim., simulated; avg., average; ROS, rate of spread; FL, flame length. Values of KC followed by ** indicate significant accuracy with respect to chance agreement at $P \leq 0.01$

Case study	Fuel type (fuel model)	KC	SC	OI	Obs. fire size (ha)	Sim. fire size (ha)	Avg. ROS (m min^{-1})	Max. ROS (m min^{-1})	Avg. FL (m)	Max. FL (m)
Alexandroupoli	Agricultural areas (CMA4)	0.42**	0.50	0.72	8.3	17.2	2.2	8.6	0.2	0.2
	Dense shrublands (CMA1)	0.73**	0.76	0.76	42.2	61.9	3.7	17.3	6.1	19.0
	Grasslands (CMA3)	0.78**	0.80	0.65	15.7	20.4	2.9	10.6	0.4	0.5
	Very low, seasonal shrubs (CMA2)	0.68**	0.78	−0.69	57.6	44.4	1.5	6.9	0.8	1.2
Attica	Agricultural areas (GS2)	0.65**	0.80	0.73	1496.6	2220.4	0.6	39.0	1.0	3.0
	Grasslands (FM1)	0.65**	0.80	0.45	481.9	569.3	8.8	39.0	0.6	16.0
	Pinus halepensis stands without shrub layer (FM3)	0.54**	0.69	0.73	870.8	1614.9	14.7	60.0	4.1	16.0
	Pinus stands with moderately dense *Quercus* shrubs (FM6)	0.78**	0.81	0.78	460.8	796.3	3.5	19.0	0.0	14.0
	Pinus stands with tall and dense *Quercus* shrubs (FM7)	0.58**	0.68	1.00	7.0	10.3	3.1	9.0	0.9	9.0
	Quercus coccifera maquis and *Pinus halepensis* stands (FM4)	0.56**	0.72	0.98	3722.9	5745.9	11.0	64.0	7.0	24.0
Budoni	Grasslands (FM1)	0.60**	0.61	1.00	9.6	8.0	10.8	52.1	1.9	8.8
	High-load maquis (CMB2)	0.60**	0.66	0.00	109.3	179.0	7.6	72.0	2.9	10.5
	Low-load maquis (CMB1)	0.58**	0.65	−1.00	21.8	42.0	3.3	43.6	1.3	8.3
Collado	*Agrostis* grasslands (FM1)	0.00	0.00	−0.69	1.0	0.2	13.0	13.0	8.0	8.0
	High *Cytisus multiflorus* shrubs (CME5)	0.72**	0.79	−0.18	115.2	110.3	7.3	19.0	3.7	10.0
	High *Cytisus scoparius* shrubs (FM4)	0.16**	0.24	1.00	80.6	328.8	18.5	38.0	9.3	18.0
	High-load *Pinus* understorey (FM9)	0.00	0.00	1.00	0.0	2.3	0.5	1.0	0.0	0.0
	Holcus grasslands (FM2)	0.31**	0.39	0.99	37.2	68.9	13.1	29.0	7.5	14.0
	Medium-height *Cytisus multiflorus* shrubs (FM7)	0.86**	0.94	−0.38	47.5	46.8	9.0	18.0	4.1	8.0
	Medium heigth *Cytisus scoparius* shrubs (FM6)	0.60**	0.66	0.95	91.5	155.7	9.0	18.0	4.4	10.0
Fresnedoso de Ibor	High *Cistus ladanifer* shrubs (FM4)	0.46**	0.49	0.91	119.2	282.9	51.5	105.0	20.5	40.0
	High *Cytisus multiflorus* shrubs (CME5)	0.40**	0.40	0.94	2.7	9.6	11.2	31.0	5.7	16.0
	Holcus grasslands (FM2)	0.68**	0.72	−0.50	60.2	33.2	16.9	70.0	6.1	28.0
	Low-load *Pinus* understorey (FM8)	0.08	0.05	−0.05	2.0	1.8	0.0	0.0	0.0	0.0
	Medium-height *Cistus ladanifer* shrubs (FM6)	0.17**	0.17	1.00	0.7	7.3	16.0	31.0	4.6	10.0
	Quercus shrubs (FM7)	0.62**	0.68	0.99	16.2	25.7	12.0	37.0	6.4	17.0
Hurdes	High *Cytisus multiflorus* shrubs (CME5)	0.75**	0.79	0.11	473.8	495.8	10.1	22.0	5.7	11.0
	High *Cytisus scoparius* shrubs (FM4)	0.98**	0.98	−0.14	548.1	546.6	29.5	59.0	14.4	28.0
	High-load *Pinus* understorey (FM9)	0.73**	0.75	−0.86	88.0	57.2	4.3	9.0	0.5	1.0
	Holcus grasslands (FM2)	0.61**	0.66	−0.91	89.6	13.8	14.7	47.0	7.1	24.0
	Low-load *Pinus* understorey (FM8)	0.84**	0.89	−0.97	192.9	156.5	4.1	9.0	0.5	1.0
	Medium-height *Cytisus scoparius* shrubs (FM6)	0.75**	0.80	0.95	1655.9	2459.1	19.3	50.0	11.5	23.0
Lochiri	Broadleaf stands (CMS6B)	0.63**	0.71	0.97	898.9	1568.3	6.2	39.0	9.4	46.0
	Garrigue (CMS2)	0.07	0.07	1.00	2.6	72.8	6.0	33.0	1.8	8.0
	Grasslands (CMS4G)	0.61**	0.68	0.96	1343.2	2420.8	5.1	24.0	0.5	8.0
	Mediterranean maquis (CMS3)	0.48**	0.51	0.99	171.0	487.7	5.9	32.0	9.1	36.0
	Open pastures (CMS1)	0.79**	0.81	1.00	10.1	14.8	11.8	36.0	1.0	5.0
	Orchards (CMS4O)	0.81**	0.85	0.87	91.8	118.6	7.5	27.0	0.7	18.0
	Pinus stands (CMS5)	0.06	0.06	1.00	2.4	81.3	8.4	26.0	11.6	36.0
Monte Doglia	High and close maquis (CMM1)	0.75**	0.80	1.00	28.3	42.5	6.0	30.3	2.8	6.7
	Medium-height and open maquis (CMM2)	0.66**	0.70	0.00	41.8	68.5	6.5	37.6	3.0	7.5
Navalmoral	*Agrostis* grasslands (FM1)	0.70**	0.75	0.94	24.1	31.1	20.5	41.0	10.4	20.0
	Cytisus multiflorus shrubs (CME5)	0.84**	0.86	0.95	62.2	73.4	24.5	48.0	11.4	22.0
	Holcus grasslands (FM2)	0.00	0.00	1.00	0.0	3.2	8.3	19.0	0.5	1.0
Nuoro	Broadleaf stands (CMS6B)	0.77**	0.81	0.12	2361.1	2492.0	6.1	33.0	6.9	27.0
	Garrigue (CMS2)	0.74**	0.78	−0.11	392.8	374.5	5.6	31.0	1.9	11.0

(*Continued*)

Table 4. (Continued)

Case study	Fuel type (fuel model)	KC	SC	OI	Obs. fire size (ha)	Sim. fire size (ha)	Avg. ROS (m min^{-1})	Max. ROS (m min^{-1})	Avg. FL (m)	Max. FL (m)
	Grasslands (CMS4G)	0.72**	0.76	−0.27	1026.0	896.5	6.2	34.0	0.6	9.0
	Mediterranean maquis (CMS3)	0.78**	0.83	−0.12	1671.5	1598.5	9.2	37.0	7.8	24.0
	Mixed woods (CMS6W)	0.42**	0.53	−0.74	178.5	86.0	6.2	20.0	6.6	20.0
	Open pastures (CMS1)	0.72**	0.78	−0.30	1203.0	1049.3	11.0	42.0	0.7	7.0
	Orchards (CMS4O)	0.68**	0.70	−0.43	183.8	142.0	8.6	38.0	0.8	8.0
	Pinus stands (CMS5)	0.74**	0.78	0.20	443.3	483.5	7.6	45.0	6.9	27.0
Penteli	Dense shrublands (CMP1)	0.85**	0.93	0.31	941.4	961.1	6.3	98.0	15.7	34.0
	Grasslands (CMP4)	0.79**	0.82	0.94	13.8	19.7	9.6	111.0	4.2	7.0
	Non-burnable areas (NB)	0.24	0.29	−0.99	516.1	87.9	0.0	0.0	0.0	0.0
	Sparse shrublands (CMP2)	0.80**	0.89	−0.36	2000.7	1975.5	2.8	111.0	2.2	34.0
	Understorey of *Pinus* stands (CMP3)	0.57**	0.65	−0.64	248.0	164.8	1.8	58.0	1.1	10.0
Vall de Gallinera	Agricultural areas with significant natural vegetation (GS1)	0.02	0.02	−1.00	31.4	0.3	0.2	1.0	0.2	1.0
	Dense shrublands (CMV2)	0.85**	0.87	0.00	393.4	423.5	1.9	4.0	2.1	5.0
	Irrigated agricultural areas and fruit trees (GR1)	0.00	0.00	−1.00	10.1	0.0	0.0	0.0	0.0	0.0
	Low-density shrublands (CMV1)	0.56**	0.59	−0.50	83.3	40.7	0.1	4.0	0.1	4.0
	Shrublands with sparse trees (*Pinus* and *Quercus*) (SH5)	1.00**	1.00	0.00	52.1	52.1	0.7	3.0	0.7	3.0
	Urban areas with very low fuel load (NB)	0.00	0.00	−1.00	20.6	0.0	0.0	0.0	0.0	0.0

zones; thus, lower-intensity areas were selectively eliminated from the fire area by suppression activities. In the other case studies in which barriers were not used, clear differences in FL estimates among simulations were observed, with the highest values simulated in the Lochiri and Nuoro fires (average FL $>$ 5 m). The lowest average FL values were obtained in Vall de Gallinera (1.8 m) and in Alexandroupoli (2.4 m) events.

The comparison among simulations, summarised for different fuel type classes and slope ranges, showed that all simulations estimated the spatial extent of burned and unburned areas better than random chance at $P \leq 0.01$ (Tables 3 and 4), with the exception of some minor fuel types. Except for fuel models covering very small areas, KC and SC values were above 0.50 for most of the fuel models used (Table 4) and the lowest agreement between actual and simulated fires in terms of fuel types was observed in the case study of Collado for 'Holcus grasslands' (FM2) (KC = 0.31; SC = 0.39) and 'High *Cytisus scoparius* shrubs' (FM4) (KC = 0.16; SC = 0.24), both of which showed errors of overestimation (OI $\geq$ 0.99) (Table 4); also, 'Agricultural areas with significant natural vegetation' (GS1) in the case study of Vall de Gallinera showed very low KC and SC values (KC = 0.02; SC = 0.02) due to underestimation errors (OI = 1.00). Other fuel types that presented relatively low KC and SC values were shrublands (FM4 in Fresnedoso de Ibor, CMS3 in Lochiri), forest understorey (CMS6W in Nuoro) and agricultural areas (CMA4 in Alexandroupoli) (Table 4). The limited agreement between observation and simulation for these fuel types can be explained by an inappropriate assignment of fuel model characteristics, an incomplete description of the suppression activities and the limitations of Rothermel's model. In several cases, the fuel types with a predominance of herbaceous vegetation presented average ROS values higher than the other types, and were also distinguishable by a significantly lower average FL value (Table 4). In contrast, conifer and broadleaf understorey types were characterised by lower average ROS values and higher average fire intensity than grasslands in almost all cases. High and dense shrublands (e.g. CME5; FM4) were, however, characterised by relatively high ROS and FL, especially in some case studies: this was due to the characteristics of such fuel types (low live fuel moisture, high fuel load and depth) and to the steep and degraded areas they occupy.

Regarding slope, FARSITE simulations did not show an evident relationship between slope classes and simulation accuracy (Table 5). For instance, excluding slope classes covering small areas, in some cases the most accurate SC and KC values were obtained for slopes greater than 25° (Attica, KC = 0.73; SC = 0.85; Hurdes, KC = 0.79; SC = 0.83), whereas in others, the best performance was obtained for flat areas (Lochiri, KC = 0.61; SC = 0.73; Vall de Gallinera, KC = 0.75; SC = 0.77) (Table 5). Furthermore, an unequivocal relationship between the slope class and the average or maximum ROS and FLI values was not observed, except for the Monte Doglia and Attica fires, where the average ROS increased with slope (data not shown). The lack of relationship among slope classes, ROS and FL is due to the fact that in our analysis, we did not take into account the fire spread direction, which determines relevant effects in terms of fire behaviour (e.g. backing fire downslope vs heading upslope).

Discussion

The present work illustrates the results obtained using the FARSITE simulator in quite a large set of historic fires along a transect of fire-prone southern European areas. Even if

Table 5. Simulation accuracy and fire size calculated for each case study, considering different slope classes
KC, kappa coefficient; SC, Sorensen coefficient; OI, overestimation index Obs., observed; Sim., simulated. All values of KC showed significant accuracy with respect to chance agreement at $P \leq 0.01$. The results refer to the simulations performed using the custom fuel models

Case study	Slope (°)	KC	SC	OI	Obs. fire size (ha)	Sim. fire size (ha)
Alexandroupoli	<5	0.67	0.70	0.34	18.6	23.1
	5.01–12	0.65	0.71	0.18	51.0	57.7
	12.01–25	0.73	0.78	0.31	47.4	55.3
	>25.01	0.77	0.80	0.40	6.8	8.1
Attica	<5	0.61	0.71	0.69	1441.8	2131.3
	5.01–12	0.56	0.76	0.90	3013.8	4563.8
	12.01–25	0.52	0.72	0.96	2264.5	3842.3
	>25.01	0.73	0.85	0.96	320.0	419.6
Budoni	<5	0.66	0.67	1.00	6.4	12.0
	5.01–12	0.68	0.76	0.85	53.0	79.0
	12.01–25	0.62	0.72	0.88	77.1	127.0
	>25.01	0.52	0.56	1.00	4.8	11.0
Collado	<5	0.40	0.44	0.68	77.0	169.9
	5.01–12	0.52	0.66	0.84	165.4	301.5
	12.01–25	0.43	0.69	0.99	126.0	236.3
	>25.01	0.86	0.95	1.00	4.6	5.0
Fresnedoso de Ibor	<5	0.61	0.53	0.81	24.9	56.0
	5.01–12	0.64	0.65	0.69	56.5	93.3
	12.01–25	0.47	0.54	0.68	115.9	205.9
	>25.01	0.14	0.22	0.60	3.6	9.8
Hurdes	<5	0.45	0.48	0.20	49.5	61.6
	5.01–12	0.81	0.83	−0.13	302.7	289.8
	12.01–25	0.77	0.81	0.57	1929.1	2360.8
	>25.01	0.79	0.83	0.66	810.8	1016.2
Lochiri	<5	0.61	0.73	0.86	1255.6	2015.9
	5.01–12	0.62	0.70	0.93	891.4	1581.9
	12.01–25	0.51	0.56	0.97	393.4	994.7
	>25.01	0.34	0.36	1.00	38.2	171.8
Monte Doglia	<5	0.64	0.67	1.00	11.9	25.0
	5.01–12	0.70	0.73	1.00	26.5	45.0
	12.01–25	0.81	0.83	1.00	28.9	38.0
	>25.01	0.42	0.44	0.20	2.7	3.0
Navalmoral	<5	0.73	0.77	0.96	53.8	75.7
	5.01–12	0.89	0.90	0.91	31.6	30.6
	12.01–25	0.66	0.67	1.00	0.8	1.2
	>25.01	0.23	0.23	1.00	0.0	0.2
Nuoro	<5	0.69	0.72	−0.27	943.8	813.0
	5.01–12	0.75	0.79	−0.18	3467.0	3210.0
	12.01–25	0.79	0.82	0.02	2720.5	2740.5
	>25.01	0.63	0.65	0.35	280.5	358.8
Penteli	<5	0.72	0.76	−0.38	459.0	394.0
	5.01–12	0.69	0.79	−0.59	849.0	707.0
	12.01–25	0.63	0.80	−0.55	2003.0	1778.0
	>25.01	0.42	0.68	−0.51	409.0	330.0
Vall de Gallinera	<5	0.75	0.77	−0.50	137.6	98.8
	5.01–12	0.76	0.77	0.00	144.9	125.3
	12.01–25	0.73	0.74	0.00	146.1	154.8
	>25.01	0.71	0.72	−0.33	162.3	137.7

the number of fire events analysed in this study still does not fully represent the complexity of fire conditions and vegetation in the Mediterranean basin context, the broad gradient of the events considered highlights the potential for applying spatially explicit fire modelling in Mediterranean environments.

Overall, modelling fire spread and behaviour is a complex task owing to a set of factors, including spatial and temporal heterogeneity in weather and fuels and fire suppression effects on fire propagation (Mutlu *et al.* 2008; Alexander and Cruz 2013; Taylor *et al.* 2013; Jahdi *et al.* 2015). Several previous studies validated fire spread simulators by comparing simulated fire propagation against historical fire data (Perry 1998; Fujioka 2002; Arca *et al.* 2007*b*; Filippi *et al.* 2014; Milne *et al.* 2014; Jahdi *et al.* 2015). With regard to fuels, several studies have

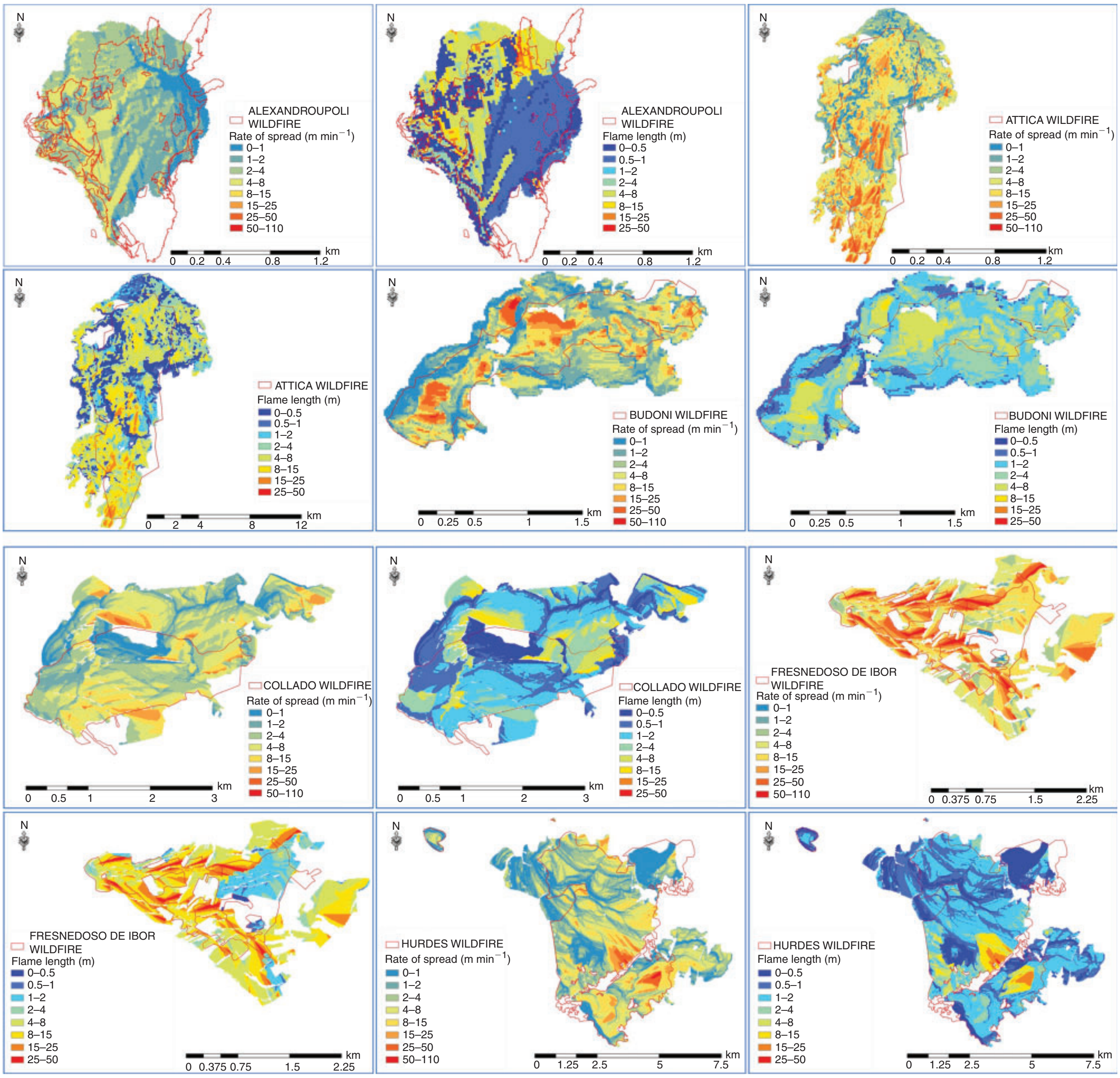

Fig. 4. Maps of the simulated fire rate of spread (m min^{-1}) and flame length (m) for each of the case studies analysed. The actual fire perimeter is the red polygon. The results refer to the simulations performed using the custom fuel models.

stressed the inadequacies and limitations of the use of standard fuel models in areas different from those in which they were developed and tested, and suggested the need for developing custom fuel models to produce more reliable predictions with fire simulators (Pastor *et al.* 2003; Arca *et al.* 2007*b*). Our work confirmed that the accuracy of FARSITE predictions can be improved by using custom fuel models. This was observed in most of the case studies, as the set of custom fuel models we applied provided a more realistic and accurate representation of the structural characteristics of the Mediterranean vegetation types, generating an increase in the accuracy of simulation results with respect to standard fuel models (Table 3). In fact, in those case studies where the customisation of fuel models was minimal (e.g. central Spain case studies), the accuracy of the simulations was lower than for the other case studies (Table 4). The improvement of the FARSITE performance driven by the use of custom models generally resulted in a reduction of overestimation errors (Table 4), owing to a better description of the local fuel characteristics.

Though in each case study, fire behaviour and spread were affected by an array of site-specific driving factors (e.g. wind speed and direction, topography, fuel moisture), our results suggested relevant differences among the main fuel types in terms of predicted ROS and FL (Table 4). Overall, the highest

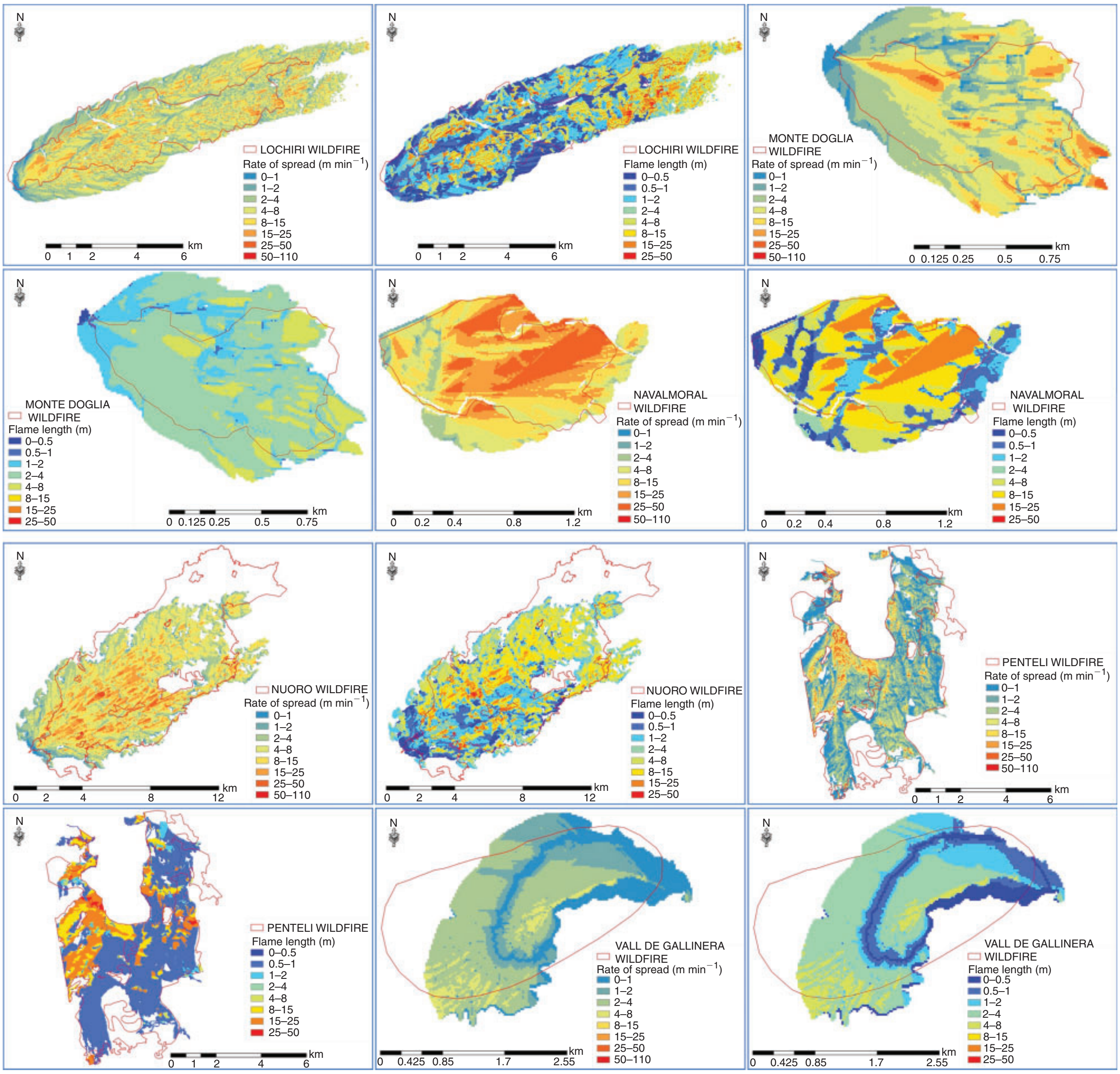

Fig. 4. (Continued)

ROS values were observed in areas covered by herbaceous vegetation, which were, however, characterised by low FL values (Table 4). In contrast, shrubs and forest vegetation types presented lower average ROS values but higher fire intensity, with the exception of some case studies where shrublands were located in steep areas and more exposed to wind. Although the case studies analysed were characterised by a complex range of fuel, topography and weather factors under which the fires burned, the values of fire spread rate and intensity obtained by FARSITE simulations for shrubland and herbaceous fuel types are similar to those reported in previous empirical studies conducted in Mediterranean ecosystems (Cruz and Viegas 1998; Massaiu 1999; Fernandes *et al.* 2000; Fernandes 2001; Bilgili and Saglam 2003; De Luis *et al.* 2004; Sağlam *et al.* 2007; Ascoli *et al.* 2007; Diana *et al.* 2011; Anderson *et al.* 2015; Arca *et al.* 2015).

We observed that FARSITE had a slightly weaker performance, as measured by SC and KC values, in areas with steep slopes (>25°) in comparison with flat areas, mainly owing to the overestimation of the actual burned surfaces (Table 5). This is in agreement with the findings of other work, which highlighted the complexity of fire propagation on steep slopes and in canyons (Viegas and Pita 2004; Viegas 2006; Sharples *et al.* 2012; Raposo *et al.* 2015).

Mass-consistent wind models can positively influence fire simulation accuracy (Arca *et al.* 2007*b*; Salis 2008; Forthofer *et al.* 2014*a*, 2014*b*). In our work, this approach was applied for all case studies, and fire simulation errors in steep areas were likely reduced through the use of a mass-consistent wind model (WindNinja) that describes wind fields in complex areas better than constant winds, because it accounts for the effects of topography on wind direction and speed (Forthofer 2007; Finney *et al.* 2009).

The fire behaviour descriptors predicted by the modelling approach proposed can support decision-making in local and regional fire prevention, monitoring and suppression plans. In addition, the data (burn probabilities, fire intensity, etc.) provided by the application of spatially explicit simulations based on different weather and landscape scenarios can guide fire management agencies in planning fuel treatment actions and locating fire-towers, water tanks and other available firefighting resources (Ager *et al.* 2010; Wu *et al.* 2013; Vogler *et al.* 2015; Salis *et al.* 2016); in near-real-time applications, these outputs may also be useful in the short-term prediction of fire growth or hazard mapping (Hollingsworth *et al.* 2012).

These simulation models, which allow spatial and temporal characterisation of fire spread and behaviour, can also be used as a tool for training and education purposes, as well as for interpreting historic fires, evaluating firefighting operations and tactics, and detecting strengths and weaknesses of specific suppression activities (Alcasena *et al.* 2016; Salis *et al.* 2016). The abovementioned output data can be integrated within a GIS to provide geospatial information on topography, fuel characteristics and weather, thus allowing detailed visualisation and in-depth analysis of fire simulation results and landscape fire behaviour analyses (e.g. Wildland Fire Decision Support System, http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml, accessed 29 June 2016). Furthermore, the development of reliable fire behaviour simulations such as those carried out in the present work can help foster collaboration among national fire-management authorities during major fire events, when firefighting resources are often transferred across countries, and thus facilitate coordinated fire suppression efforts. The characterisation of landscapes through a deeper knowledge of the properties of their fuel types, and the interactions between fuels and fire spread and behaviour can substantially help managers to perform risk evaluations and identify the most critical locations. Many studies have concluded that fuel management projects designed at a landscape scale have the potential to reduce fire intensity or burn probability, and to assist suppression efforts: fire spread models play a key role in this purpose (Duguy *et al.* 2007; Ager *et al.* 2010; Safford *et al.* 2012; Miller and Ager 2013; Ager *et al.* 2014*b*; Salis *et al.* 2016).

The availability of fire spread and behaviour simulators calibrated and validated for the vegetation characteristics of Mediterranean fire-prone ecosystems and landscapes may foster optimised designs of common fuel management practices across the Euro-Mediterranean region (Curt *et al.* 2013; Duguy *et al.* 2013; Salis *et al.* 2013, 2016; Alcasena *et al.* 2015, 2016). This would represent a crucial task for mitigation and adaptation strategies under climate change scenarios, for which the use of fire-spread modelling may play a relevant role in predicting future fire spread and behaviour, following a probabilistic approach, in areas deemed to be at high risk or highly valued.

Conclusions

In the present work, we evaluated the performance of the FARSITE simulator to predict the spread of a set of recent wildfires with different sizes occurring along an east–west gradient of the Euro-Mediterranean basin. Despite the inherent limitations and assumptions of the modelling approach, we showed that FARSITE provided realistic results in most of the case studies analysed. The experimental results confirmed the significant role played by the fuel model characteristics and slope classes on the simulated fire spread and behaviour, namely in terms of fire perimeters and size, ROS and FL, but also in terms of accuracy with respect to the actual events.

A set of customised fuel models mainly related to Mediterranean shrubland vegetation was also provided in this study. The use of the custom fuel models specifically developed for each site improved the accuracy and the reliability of the simulations in comparison with the application of standard fuel models. The whole methodology presented can be replicated for other Mediterranean areas and elsewhere to characterise fine-scale fire spread and behaviour and map fire hazard. Such an approach provides useful data to improve both short-term fire management and long-term strategic forest management activities, also from a perspective of future global changes. Moreover, it may inform fuel management practices and firefighting suppression strategies across the Euro-Mediterranean region.

Acknowledgements

This work was funded by the European Union (EU) Seventh Framework Program (FP7, grant agreement no. 243888) through the project 'FUME – Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world'. We are grateful to all those who helped in this work, particularly the Centro Operativo Regional del Plan INFOEX (COR) de la Consejería de Agricultura, Desarrollo Rural, Medio Ambiente y Energía del Gobierno de Extremadura. The work of Michele Salis was supported by the project 'Modeling approach to evaluate fire risk and mitigation planning actions' (POR Sardegna FSE 2007–2013, Asse IV Capitale Umano, Linea di Attività l.3.1).

References

Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* **259**, 1556–1570. doi:10.1016/J.FORECO.2010.01.032

Ager AA, Vaillant N, Finney MA (2011) Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. *Journal of Combustion* 572452. doi:10.1155/2011/572452

Ager AA, Preisler H, Arca B, Spano D, Salis M (2014*a*). Wildfire risk estimation in the Mediterranean area. *Environmetrics* **25**, 384–396. doi:10.1002/ENV.2269

Ager AA, Day MA, McHugh CW, Short K, Gilbertson-Day J, Finney MA, Calkin DE (2014*b*). Wildfire exposure and fuel management on western US national forests. *Journal of Environmental Management* **145**, 54–70. doi:10.1016/J.JENVMAN.2014.05.035

Agresti A (1996) 'An introduction to categorical data analysis.' (Wiley: New York)

Albini FA (1979) Spot fire distance from burning trees – a predictive model. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-56. (Ogden, UT)

Alcasena F, Salis M, Ager AA, Arca B, Molina D, Spano D (2015) Assessing fine-scale wildfire exposure for highly valued resources in a Mediterranean area. *Environmental Management* **55**, 1200–1216. doi:10.1007/S00267-015-0448-6

Alcasena F, Salis M, Vega-Garcia C (2016) A fire modeling approach to assess wildfire exposure in central Navarra, Spain. *European Journal of Forest Research* **135**, 87–107. doi:10.1007/S10342-015-0919-6

Alexander ME, Cruz MG (2013) Are the applications of wildland fire behaviour models getting ahead of their evaluation again? *Environmental Modelling & Software* **41**, 65–71. doi:10.1016/J.ENVSOFT.2012.11.001

Anderson HE (1982) Aids to determining fuel models for estimating fire behaviour. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-122. (Ogden, UT)

Anderson WR, Cruz MG, Fernandes PM, Mccaw L, Vega J, Bradstock RA, Fogarty L, Gould J, McCarthy G, Marsden-Smedley JB, Matthews S, Mattingley G, Pearce H, van Wilgen B (2015) A generic, empirical-based model for predicting rate of fire spread in shrublands. *International Journal of Wildland Fire* **24**, 443–460. doi:10.1071/WF14130

Andrews PL (1986) BEHAVE: fire behavior prediction and fuel modeling subsystem – BURN subsystem, Part 1. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR-194. (Ogden, UT)

Arca B, Bacciu V, Duce P, Pellizzaro G, Salis M, Spano D (2007*a*) Use of FARSITE simulator to produce fire probability maps in a Mediterranean area. In 'Proceedings of the 7th symposium on fire and forest meteorology', Bar Harbor, ME, 23–25 October 2007. (Ed. American Meteorological Society) Available at https://ams.confex.com/ams/pdfpapers/127440.pdf [Verified 29 June 2016]

Arca B, Duce P, Laconi M, Pellizzaro G, Salis M, Spano D (2007*b*) Evaluation of FARSITE simulator in Mediterranean maquis. *International Journal of Wildland Fire* **16**, 563–572. doi:10.1071/WF06070

Arca B, Bacciu V, Pellizzaro G, Salis M, Ventura A, Duce P, Spano D, Brundu G (2009) Fuel model mapping by IKONOS imagery to support spatially explicit fire simulators. In '7th International workshop on advances in remote sensing and GIS applications in forest fire management towards an operational use of remote sensing in forest fire management', 2–5 September 2009, Matera, Italy. (Eds E. Chuvieco, R Lasaponara) (Il Segno – Arti Grafiche, Societa' Cooperativa Sociale: Potenza, Italy)

Arca B, Ventura A, Casula M, Pintus GV, Munoz O, Jahdi R, Bacciu V, Diana G, Pirisi AM, Gruppo GAUF, Salis M (2015) Evaluating the capabilities of foams in limiting fire spread. In 'Book of abstracts of the second international conference on fire behaviour and risk', Alghero, Italy, 26–29 May 2015. (Eds P Duce, D Spano, M Vannini, A Navarra) (Euro–Mediterranean Center on Climate Change: Sassari, Italy)

Arroyo LA, Pascual C, Manzanera JA (2008) Fire models and methods to map fuel types: the role of remote sensing. *Forest Ecology and Management* **256**, 1239–1252. doi:10.1016/J.FORECO.2008.06.048

Ascoli D, Bovio G, Ceccato R, Marzano R (2007) Experimental analysis of the relationship between fire behaviour and biomass in fuel break management. *Italian Journal of Forest and Mountain Environments* **62**, 369–383. [In Italian] doi:10.4129/IFM.2007.5-6.05

Bilgili E, Saglam B (2003) Fire behavior in maquis fuels in Turkey. *Forest Ecology and Management* **184**, 201–207. doi:10.1016/S0378-1127(03)00208-1

Cai L, He HS, Wu Z, Lewis BL, Liang Y (2014) Development of standard fuel models in boreal forests of north-east China through calibration and validation. *PLoS One* **9**(4), e94043. doi:10.1371/JOURNAL.PONE.0094043

Carmel Y, Paz S, Jahashan F, Shoshany M (2009) Assessing fire risk using Monte Carlo simulations of fire spread. *Forest Ecology and Management* **257**, 370–377. doi:10.1016/J.FORECO.2008.09.039

Carvalho AC, Miranda AI, Borrego C (1997) Numerical simulation of wind field over complex terrain *Transactions on Ecology and the Environment* **13**, 273–282. Available at http://www.witpress.com/Secure/elibrary/papers/MMEP97/MMEP97027FU.pdf. [Verified 5 July 2016]

Cheyette D, Rupp TS, Rodman S (2008) Developing fire behavior fuel models for the wildland–urban interface in Anchorage, Alaska. *Western Journal of Applied Forestry* **23**, 149–155.

Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37**, 35–46. doi:10.1016/0034-4257(91)90048-B

Cruz MG, Fernandes PM (2008) Development of fuel models for fire behaviour prediction in maritime pine (*Pinus pinaster* Ait.) stands. *International Journal of Wildland Fire* **17**, 194–204. doi:10.1071/WF07009

Cruz MG, Viegas DX (1998) Fire behaviour in some common central Portugal fuel complexes: evaluation of fire behaviour models performance. In 'Proceedings of the third international conference on forest fire research/14th fire and forest meteorology conference', Luso, 16–20 November 1998. (Ed. DX Viegas) pp. 859–875. (ADAI, University of Coimbra: Coimbra)

Curt T, Borgniet L, Bouillon C (2013) Wildfire frequency varies with the size and shape of fuel types in south-eastern France: implications for environmental management. *Journal of Environmental Management* **117**, 150–161. doi:10.1016/J.JENVMAN.2012.12.006

De Luis M, Baeza MJ, Raventós J, Hidalgo JCG (2004) Fuel characteristics and fire behavior in mature Mediterranean gorse shrublands. *International Journal of Wildland Fire* **13**, 79–87. doi:10.1071/WF03005

Deeming JE, Lancaster JW, Fosberg MA, Furman RW, Schroeder MJ (1972) The National Fire Danger Rating System. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RM-84. (Fort Collins, CO)

Diana G, Salis M, Farris G, Farris O, Licheri F, Musina G, Peluffo L, Orotelli S, Pirisi AM, Bacciu V, Casula F, Fois C, Sirca C, Spano D (2011) Prescribed burning and tactical fires potential effects on fire risk mitigation: the Sardinian experience. In 'Proceedings of the international conference on fire behaviour and risk', Alghero, Italy, 4–6 October 2011. (Eds D Spano, P Duce) (TAS Tipografi Associati Sassari: Sassari, Italy)

Dimitrakopoulos AP (2001) A statistical classification of Mediterranean species based on their flammability components. *International Journal of Wildland Fire* **10**, 113–118. doi:10.1071/WF01004

Dimitrakopoulos AP (2002) Mediterranean fuel models and potential fire behavior in Greece. *International Journal of Wildland Fire* **11**, 127–130. doi:10.1071/WF02018

Dimitrakopoulos AP, Panov PI (2001) Pyric properties of some dominant Mediterranean vegetation species. *International Journal of Wildland Fire* **10**, 23–27. doi:10.1071/WF01003

Dimitrakopoulos AP, Gogi C, Stamatelos G, Mitsopoulos I (2011) Statistical analysis of fire environment of large forest fires (>1000 ha) in Greece. *Polish Journal of Environmental Studies* **20**, 327–332.

Duguy B, Vallejo VR (2008) Land-use and fire history effects on post-fire vegetation dynamics in eastern Spain. *Journal of Vegetation Science* **19**, 97–108. doi:10.3170/2007-8-18336

Duguy B, Alloza JA, Röder A, Vallejo R, Pastor F (2007) Modeling the effects of landscape fuel treatments on fire growth and behaviour in a Mediterranean landscape (eastern Spain). *International Journal of Wildland Fire* **16**, 619–632. doi:10.1071/WF06101

Duguy B, Paula S, Pausas JG, Alloza JA, Gimeno T, Vallejo VR (2013) Effects of climate and extreme events on wildfire regime and their ecological impacts. In 'Regional assessment of climate change in the Mediterranean, Vol. 2: Agriculture, forests and ecosystem services and people'. Advances in Global Change Research (Eds A Navarra, L Tubiana L) pp. 101–134. (Springer Science+Business Media: Dordrecht, the Netherlands)

EEA (2002) CORINE land cover update 2000 – technical guidelines. European Environment Agency, Technical Report 89. (European Environment Agency: Copenhagen, Denmark). Available at http://land.copernicus.eu/user-corner/technical-library/techrep89.pdf [Verified 5 July 2016].

Fernandes PAM (2001) Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management* **144**, 67–74. doi:10.1016/S0378-1127(00)00363-7

Fernandes PM, Catchpole WR, Rego FC (2000) Shrubland fire behaviour modelling with microplot data. *Canadian Journal of Forest Research* **30**, 889–899. doi:10.1139/X00-012

Filippi J-B, Morandini F, Balbi JH, Hill DR (2010) Discrete event front-tracking simulation of a physical fire-spread model. *Simulation* **86**, 629–646. doi:10.1177/0037549709343117

Filippi J-B, Mallet V, Nader B (2014) Representation and evaluation of wildfire propagation simulations. *International Journal of Wildland Fire* **23**, 46–57. doi:10.1071/WF12202

Finney MA (1998) FARSITE: Fire Area Simulator – model development and evaluation. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-4. (Fort Collins, CO)

Finney MA (2002) Fire growth using minimum travel time methods. *Canadian Journal of Forest Research* **32**, 1420–1424. doi:10.1139/X02-068

Finney MA, Bradshaw L, Butler B (2009) Delivery and demonstration of surface wind simulation tool for fire management decision support. Joint Fire Science Program Research Project Reports, Paper 109. Available at http://digitalcommons.unl.edu/jfspresearch/109 [Verified 29 June 2016]

Foody GM (2004) Thematic map comparison: evaluating the statistical significance of differences in classification accuracy. *Photogrammetric Engineering and Remote Sensing* **70**, 627–633. doi:10.14358/PERS.70.5.627

Forthofer JM (2007) Modeling wind in complex terrain for use in fire spread prediction. MSc Thesis, Colorado State University, Fort Collins, CO.

Forthofer JM, Butler BW (2007) Differences in simulated fire spread over Askervein Hill using two advanced wind models and a traditional uniform wind field. In 'The fire environment – innovations, management, and policy; conference proceedings', 26–30 March 2007, Destin, FL. (Eds BW Butler, W Cook) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-46CD, pp. 123–127. (Fort Collins, CO)

Forthofer JM, Butler BW, Wagenbrenner NS (2014*a*). A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part I. Model formulation and comparison against measurements. *International Journal of Wildland Fire* **23**, 969–981. doi:10.1071/WF12089

Forthofer JM, Butler BW, McHugh CW, Finney MA, Bradshaw LS, Stratton RD, Shannon KS, Wagenbrenner NS (2014*b*). A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part II. An exploratory study of the effect of simulated winds on fire growth simulations. *International Journal of Wildland Fire* **23**, 982–994. doi:10.1071/WF12090

Fujioka FM (2002) A new method for the analysis of fire spread modeling errors. *International Journal of Wildland Fire* **11**, 193–203. doi:10.1071/WF02004

Ganteaume A, Jappiot M (2013) What causes large fires in southern France. *Forest Ecology and Management* **294**, 76–85. doi:10.1016/J.FORECO.2012.06.055

Hollingsworth LT, Kurth LL, Parresol BR, Ottmar RD, Prichard SJ (2012) A comparison of geospatially modeled fire behavior and fire management utility of three data sources in the south-eastern United States. *Forest Ecology and Management* **273**, 43–49. doi:10.1016/J.FORECO.2011.05.020

INFC (2005) Inventario nazionale delle foreste e dei serbatoi forestali di carbonio. Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. Ministero delle Politiche Agricole Alimentari e Forestali, Ispettorato Generale – Corpo Forestale dello Stato. Consiglio per la Ricerca e Sperimentazione in Agricoltura Unità di ricerca per il Monitoraggio e la Pianificazione Forestale (CRA-MPF). Available at http://www.sian.it/inventarioforestale/jsp/condizioni_uso.jsp [Verified 29 June 2016]

Jahdi R, Salis M, Darvishsefat AA, Mostafavi MA, Alcasena F, Etemad V, Lozano O, Spano D (2015) Calibration of FARSITE simulator in northern Iranian forests. *Natural Hazards and Earth System Sciences* **15**, 443–459. doi:10.5194/NHESS-15-443-2015

Jahdi R, Salis M, Darvishsefat AA, Alcasena FJ, Mostafavi MA, Etemad V, Lozano OM, Spano D (2016) Evaluating fire modelling systems in recent wildfires of the Golestan National Park, Iran. *Forestry* **89**, 136–149. doi:10.1093/FORESTRY/CPV045

Kalabokidis K, Palaiologou P, Gerasopoulos E, Giannakopoulos C, Kostopoulou E, Zerefos C (2015) Effect of climate change projections on forest fire behavior and values-at-risk in south-western Greece. *Forests* **6**, 2214–2240. doi:10.3390/F6062214

Keane RE, Burgan R, van Wagtendonk J (2001) Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire* **10**, 301–319. doi:10.1071/WF01028

Koutsias N, Arianoutsou M, Kallimanis AS, Mallinis G, Halley JM, Dimopoulos P (2012) Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather. *Agricultural and Forest Meteorology* **156**, 41–53. doi:10.1016/J.AGRFORMET.2011.12.006

Linn R, Reisner J, Colman JJ, Winterkamp J (2002) Studying wildfire behavior using FIRETEC. *International Journal of Wildland Fire* **11**, 233–246. doi:10.1071/WF02007

Linn R, Winterkamp J, Edminster C, Colman JJ, Smith WS (2007) Coupled influences of topography and wind on wildland fire behaviour. *International Journal of Wildland Fire* **16**, 183–195. doi:10.1071/WF06078

Massaiu A (1999) Il fuoco come tecnica di gestione territoriale. Applicazione di fuoco prescritto in Sardegna. BSc thesis, University of Florence, Italy. Available at Univeristy of Florence library.

Miller C, Ager AA (2013) A review of recent advances in risk analysis for wildfire management. *International Journal of Wildland Fire* **22**, 1–14. doi:10.1071/WF11114

Miller JD, Yool SR (2002) Modeling fire in semi-desert grassland/oak woodland: the spatial implications. *Ecological Modelling* **153**, 229–245. doi:10.1016/S0304-3800(02)00015-7

Milne GJ, Kelso JK, Mellor D, Murphy ME (2014) Evaluating wildfire simulators using historical fire data. In 'Advances in forest fire research'. (Ed. DX Viegas) pp. 1366–1375. (Imprensa da Universidade de Coimbra: Coimbra, Portugal). doi:10.14195/978-989-26-0884-6_150

Ministerio de Agricultura (2007) Tercer Inventario Forestal Nacional (IFN3). Available at http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3.aspx [Verified 5 July 2016]

Mitsopoulos I, Mallinis G, Arianoutsou M (2015) Wildfire risk assessment in a typical Mediterranean wildland–urban interface of Greece. *Environmental Management* **55**, 900–915. doi:10.1007/S00267-014-0432-6

Mitsopoulos ID, Dimitrakopoulos AP (2014) Estimation of canopy fuel characteristics of Aleppo pine (*Pinus halepensis* Mill.) based on common stand parameters. *European Journal of Forest Research* **133**, 73–79. doi:10.1007/S10342-013-0740-Z

Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot E, Barbati A, Corona P, Vaz P, Xanthopoulos G, Mouillot F, Bilgili E

(2011) Landscape–wildfire interactions in southern Europe: implications for landscape management. *Journal of Environmental Management* **92**, 2389–2402. doi:10.1016/J.JENVMAN.2011.06.028

Moreno JM, Viedma O, Zavala G, Luna B (2011) Landscape variables influencing forest fires in central Spain. *International Journal of Wildland Fire* **20**, 678–689. doi:10.1071/WF10005

Mutlu M, Popescu SC, Zhao K (2008) Sensitivity analysis of fire behavior modeling with LIDAR-derived surface fuel maps. *Forest Ecology and Management* **256**, 289–294. doi:10.1016/J.FORECO.2008.04.014

Papadopoulos GD, Pavlidou FN (2011) A comparative review on wildfire simulators. *IEEE Systems Journal* **5**, 233–243. doi:10.1109/JSYST.2011.2125230

Pastor E, Zarate 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. doi:10.1016/S0360-1285(03)00017-0

Pausas JG, Fernández-Muñoz S (2012) Fire regime changes in the western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change* **110**, 215–226. doi:10.1007/S10584-011-0060-6

Pausas JG, Vallejo R (1999) The role of fire in European Mediterranean ecosystems. In 'Remote sensing of large wildfires in the European Mediterranean basin'. (Ed. E Chuvieco) pp. 3–16. (Springer: Berlin).

Paz S, Carmel Y, Jahshan F, Shoshany M (2011) Post-fire analysis of pre-fire mapping of fire risk: a recent case study from Mt Carmel (Israel). *Forest Ecology and Management* **262**, 1184–1188. doi:10.1016/J.FORECO.2011.06.011

Pellizzaro G, Duce P, Ventura A, Zara P (2007) Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. *International Journal of Wildland Fire* **16**, 633–641. doi:10.1071/WF05088

Pereira MG, Trigo RM, da Camara CC, Pereira JMC, Leite SM (2005) Synoptic patterns associated with large summer forest fires in Portugal. *Agricultural and Forest Meteorology* **129**, 11–25. doi:10.1016/J.AGRFORMET.2004.12.007

Perry GLW (1998) Current approaches to modelling the spread of wildland fire: a review. *Progress in Physical Geography* **22**, 222–245. doi:10.1177/030913339802200204

Raposo JR, Cabiddu S, Viegas DX, Salis M, Sharples J (2015) Experimental analysis of fire spread across a two-dimensional ridge under wind conditions. *International Journal of Wildland Fire*. doi:10.1071/WF14150

Rodríguez y Silva F, Molina-Martínez JR (2012) Modeling Mediterranean forest fuels by integrating field data and mapping tools. *European Journal of Forest Research* **131**, 571–582. doi:10.1007/S10342-011-0532-2

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115 (Ogden, UT).

Safford HD, Stevens JT, Merriam K, Meyer MD, Latimer AM (2012) Fuel treatment effectiveness in California yellow pine and mixed-conifer forests. *Forest Ecology and Management* **274**, 17–28. doi:10.1016/J.FORECO.2012.02.013

Sağlam B, Küçük Ö, Bilgili E, Dinç Durmaz B, Baysal I (2007) Preliminary results of fire behavior in maquis fuels under varying weather and slope conditions in Turkey. In 'The fire environment – innovations, management, and policy; conference proceedings', 26–30 March 2007, Destin, FL. (Comps BW Butler, W Cook). USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-46CD, pp. 249– 254. (CD-ROM) (Fort Collins, CO)

Sağlam B, Küçük Ö, Bilgili E, Dinç Durmaz B, Baysal I (2008) Estimating fuel biomass of some shrub (maquis) species in Turkey. *Turkish Journal of Agriculture and Forestry* **32**, 349–356.

Salis M (2008) Fire behaviour simulation in Mediterranean maquis using FARSITE (Fire Area Simulator). PhD thesis, Università degli Studi di Sassari, Italy. Available at http://eprints.uniss.it/23/ [Verified 29 June 2016]

Salis M, Ager AA, Arca B, Finney MA, Bacciu V, Duce P, Spano D (2013) Assessing exposure of human and ecological values to wildfire in Sardinia, Italy. *International Journal of Wildland Fire* **22**, 549–565. doi:10.1071/WF11060

Salis M, Ager AA, Arca B, Finney MA, Spano D (2014) Analyzing spatiotemporal changes in wildfire regime and exposure across a Mediterranean fire-prone area. *Natural Hazards* **71**, 1389–1418. doi:10.1007/S11069-013-0951-0

Salis M, Ager AA, Alcasena F, Arca B, Finney MA, Pellizzaro G, Spano D (2015) Analyzing seasonal patterns of wildfire likelihood and intensity in Sardinia, Italy. *Environmental Monitoring and Assessment* **187**, 4175. doi:10.1007/S10661-014-4175-X

Salis M, Laconi M, Ager AA, Arca B, Lozano O, Fernandes de Oliveira A, Spano D (2016) Evaluating competing fuel treatment strategies to reduce wildfire losses in a Mediterranean area. *Forest Ecology and Management* **368**, 207–221. doi:10.1016/J.FORECO.2016.03.009

Santoni PA, Balbi JH, Dupuy JL (1999) Dynamic modeling of upslope fire growth. *International Journal of Wildland Fire* **9**, 285–292. doi:10.1071/WF00004

Santoni PA, Filippi JB, Balbi JH, Bosseur F (2011) Wildland fire behaviour case studies and fuel models for landscape-scale fire modeling. *Journal of Combustion* **2011**, 613424. doi:10.1155/2011/613424

Schmuck G, San-Miguel-Ayanz J, Camia A, Durrant TH, Santos de Oliveira S, Boca R, Whitmore C, Giovando C, Libertá G, Corti P, Schulte E (2011) Forest fires in Europe 2010 (Report No. 11). (Publications Office of the European Union: Lusembourg). doi:10.2788/46294

Scott JH, Burgan R (2005) Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO)

Sharples JJ, McRae RHD, Wilkes SR (2012) Wind–terrain effects on the propagation of wildfires in rugged terrain: fire channelling. *International Journal of Wildland Fire* **21**, 282–296. doi:10.1071/WF10055

Sorensen TA (1948) A method of establishing groups of equal amplitude in plant sociology based on similarity of species content, and its application to analyses of the vegetation on Danish commons *Kongelige Danske Videnskabernes Selskab – Biologiske Skrifter* **5**, 1–34.

Stratton RD (2006) Guidance on spatial wildland fire analysis: models, tools, and techniques. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-183. (Fort Collins, CO)

Sullivan AL (2009*a*). Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire* **18**, 349–368. doi:10.1071/WF06143

Sullivan AL (2009*b*). Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models. *International Journal of Wildland Fire* **18**, 387–403. doi:10.1071/WF06144

Taylor SW, Woolford DG, Dean CB, Martell DL (2013) Wildfire prediction to inform fire management: statistical science challenges. *Statistical Science* **28**, 586–615. doi:10.1214/13-STS451

Vega-Garcia C, Duguy B, Pilar Monfort I, Costafreda-Aumedes S (2014) Characterization of custom fuel models for supporting fire modeling-based optimization of prescribed fire planning in relation to wildfire prevention (southern Catalonia, Spain). In 'Advances in forest fire research'. (Ed. DX Viegas) Available at https://digitalis.uc.pt/en/livro/characterization_custom_fuel_models_supporting_fire_modeling_based_optimization_prescribed [Verified 5 July 2016]

Viedma O, Moity N, Moreno JM (2015) Changes in landscape fire-hazard during the second half of the 20th century: agriculture abandonment and the changing role of driving factors. *Agriculture, Ecosystems & Environment* **207**, 126–140. doi:10.1016/J.AGEE.2015.04.011

Viegas DX (2004) Slope and wind effects on fire propagation. *International Journal of Wildland Fire* **13**, 143–156. doi:10.1071/WF03046

Viegas DX (2006) Parametric study of an eruptive fire behaviour model. *International Journal of Wildland Fire* **15**, 169–177. doi:10.1071/WF05050

Viegas DX, Pita LP (2004) Fire spread in canyons. *International Journal of Wildland Fire* **13**, 253–274. doi:10.1071/WF03050

Viegas DX, Simeoni A, Xanthopoulos G, Rossa C, Ribeiro LM, Pita LP, Stipanicev D, Zinoviev A, Weber R, Dold J, Caballero D, San-Miguel-Ayanz J (2009) 'Recent forest fire-related accidents in Europe' pp. 1018–5593. (Luxembourg: Office for Official Publications of the European Communities) Available at http://forest.jrc.ec.europa.eu/media/cms_page_media/82/recent-forest-fire-related-accidents-in-europe.pdf [Verified 5 July 2016]

Vogler KC, Ager AA, Day MA, Jennings M, Bailey JD (2015) Prioritization of forest restoration projects: tradeoffs between wildfire protection, ecological restoration and economic objectives. *Forests* **6**, 4403–4420. doi:10.3390/F6124375

Weise DR, Biging GS (1997) A qualitative comparison of fire spread models incorporating wind and slope effects. *Forest Science* **43**, 170–180.

Werth PA, Potter BE, Clements CB, Finney MA, Goodrick SL, Alexander ME, Cruz MG, Forthofer JA, McAllister SS (2011) Synthesis of knowledge of extreme fire behavior: Vol. I for fire managers. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-854. (Portland, OR)

Wu Z, He H, Liu Z, Liang Y (2013) Comparing fuel reduction treatments for reducing wildfire size and intensity in a boreal forest landscape of north-eastern China. *The Science of the Total Environment* **454–455**, 30–39. doi:10.1016/J.SCITOTENV.2013.02.058

Xystrakis F, Koutsias N (2013) Differences of fire activity and their underlying factors among vegetation formations in Greece *i-Forest Biogeosciences and Forestry* **6**, 132–140. doi:10.3832/IFOR0837-006