

Assessing exposure of human and ecological values to wildfire in Sardinia, Italy

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Abstract. We used simulation modelling to analyse spatial variation in wildfire exposure relative to key social and economic features on the island of Sardinia, Italy. Sardinia contains a high density of urban interfaces, recreational values and highly valued agricultural areas that are increasingly being threatened by severe wildfires. Historical fire data and wildfire simulations were used to estimate burn probabilities, flame length and fire size. We examined how these risk factors varied among and within highly valued features located on the island. Estimates of burn probability excluding non-burnable fuels, ranged from $0\text{--}1.92 \times 10^{-3}$, with a mean value of 6.48×10^{-5} . Spatial patterns in modelled outputs were strongly related to fuel loadings, although topographic and other influences were apparent. Wide variation was observed among the land parcels for all the key values, providing a quantitative approach to inform wildfire risk management activities.

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Introduction

Wildfires are a growing threat to human and ecological values worldwide, particularly in the fire-prone areas of the Mediterranean Basin. The ecosystems of this region have experienced an increasing occurrence of severe and extreme fire seasons (Moreno *et al.* 1998; Mouillot and Field 2005; Trigo *et al.* 2006; Viegas *et al.* 2006; Riaño *et al.* 2007) and, as in many other areas, wildfire activity is expected to continue to increase in the future due to predicted changes in climate and land use (Thonicke *et al.* 2001; Moriondo *et al.* 2006; IPCC 2007; Arca *et al.* 2010). In the period 2000–2009, countries of south-western Europe (Italy, France, Spain, Portugal and Greece) experienced $\sim 57\,000$ wildfires year⁻¹, which burned $\sim 430\,000$ ha year⁻¹ (JRC–IES 2010). It is estimated that 90% of fires were caused by human factors such as arson and negligence.

The growing incidence of wildfires and related losses in the Mediterranean region has prompted the development of several approaches for analysing and mapping wildfire hazard, risk and exposure (Chuvieco *et al.* 2003, 2010; Carmel *et al.* 2009;

Martínez *et al.* 2009; Verde and Zezere 2010). In this paper, we define hazard as the potential for loss, risk as the expected loss and exposure as the proximity to causative risk factors (Fairbrother and Turnley 2005; Finney 2005). We define risk factors as the individual contributing components to risk (likelihood, intensity and susceptibility). Formal, quantitative assessment of wildfire risk requires (i) the probability of a fire at a specific location; (ii) the conditional fire intensity, measured in terms of flame length and (iii) the resulting change in financial or ecological value (Finney 2005). From a risk standpoint, it is important to note that a very small proportion of fires (<5%) globally accounts for most of the burned area, as well as resulting damages and human casualties (Pereira *et al.* 2005; FAO 2007; San-Miguel-Ayanz and Camia 2009). Thus, accounting for the risk posed by large destructive fires requires consideration of their behaviour and spread over large areas. Most risk models use ignition frequency or localised spread estimates (Chuvieco *et al.* 2010; Verde and Zezere 2010) that are well suited to inform the likelihood of an ignition and localised fire behaviour, but contain little information about actual



Fig. 1. Location of the island of Sardinia, Italy.

expected losses from a large fire that escapes initial attack (Finney *et al.* 2005). Estimating the expected losses from large fires requires at a minimum the consideration of fire spread across landscapes, intensity and the estimation of spatially explicit burn probabilities. Effects of large fires are now being considered as part of risk and exposure assessments in the US and Canada through the use of simulation methods (Ager *et al.* 2011; Finney *et al.* 2011; Thompson *et al.* 2011). The work is made possible by efficient fire spread algorithms incorporated into models like FlamMap and FSIM (Finney 2006; Finney *et al.* 2011) that make it possible to saturate landscapes with simulated fire events and to estimate the burn probability at different fire intensities. The products from these assessments in the US have been used in a range of policy and planning problems, including fuel management, preparedness and suppression strategies.

Despite several previous studies in the Mediterranean region that have leveraged wildfire simulations (Caballero *et al.* 1999; Arca *et al.* 2007a; Carmel *et al.* 2009), burn probability modelling has not been explored to examine spatial patterns in risk posed specifically by large fires. Most of the previous work on wildfire risk has concerned the identification of ignitions patterns and their causal factors (Cattri *et al.* 2009; Martínez *et al.* 2009). In this work, we employed simulation methods to assess landscape patterns of exposure of key human and ecological values to wildfires on the island of Sardinia, Italy. The work advances the application of wildfire simulation and risk analysis to potential effects from large (>100 ha) fires, considering historical weather, spatial ignition patterns and fuels.

Methods

Study area

Sardinia, Italy, is located in the western part of the Mediterranean Basin, between 38°50'–41°50'N latitude and

8°00'–10°00'E longitude (Fig. 1). Sardinia is divided into eight provinces and has ~1.7 million inhabitants, mostly concentrated in the provinces of Cagliari and Sassari (Fig. 2a). The island orography consists of rolling hills and low mountains (Fig. 2b), with the highest point being 1850 m above sea level in the centre of the island. The climate consists of mild rainy winters, dry hot summers and a remarkable water deficit from May until September (Chessa and Delitala 1997). This water deficit generally increases from north to south and from mountainous areas to plains. Most of the annual rainfall occurs in fall and winter; annual precipitation ranges from 500 mm on the southern coastlines to 1300 mm in the mountains. The mean annual temperature ranges from 17°C in the southern coasts to 12°C in the mountainous areas. Maximum temperature peaks are higher than 30°C during the summer season. The average wind speed is moderate–high in both winter and summer seasons; west and north-west are the most frequent wind directions.

Sardinia vegetation is influenced by both physical factors and a long history of anthropogenic pressure (fires, grazing, urbanisation, agriculture, etc.). We defined the vegetation types using the Corine land cover map (EEA 2002) as shown in Fig. 3. Woodlands and forest cover ~16% of Sardinia, and are mainly represented by *Quercus ilex* L., *Q. suber* L., *Q. pubescens* Willd. and *Q. congesta* Presl. At higher elevations *Q. pubescens* Willd. is the most representative oak formation, and *Castanea sativa* Mill., *Taxus bacata* L. and *Ilex aquifolium* L. are also present. Pine plantations cover a mere 3% of the island, and include *Pinus pinea* L. and *P. halepensis* Mill., which are mainly concentrated in the coastal areas. Large areas (28%) are covered by shrublands (Mediterranean maquis and garrigue), comprised primarily of *Pistacia lentiscus* L., *Arbutus unedo* L., *Erica arborea* L., *Myrtus communis* L., *Olea europea* L. var. *sylvestris* Brot., *Phyllirea* spp., *Juniperus* spp., *Cistus* spp. and *Euphorbia* spp. Urban and anthropic areas cover ~3% of the island, whereas 49% is composed of pastures and agricultural lands.

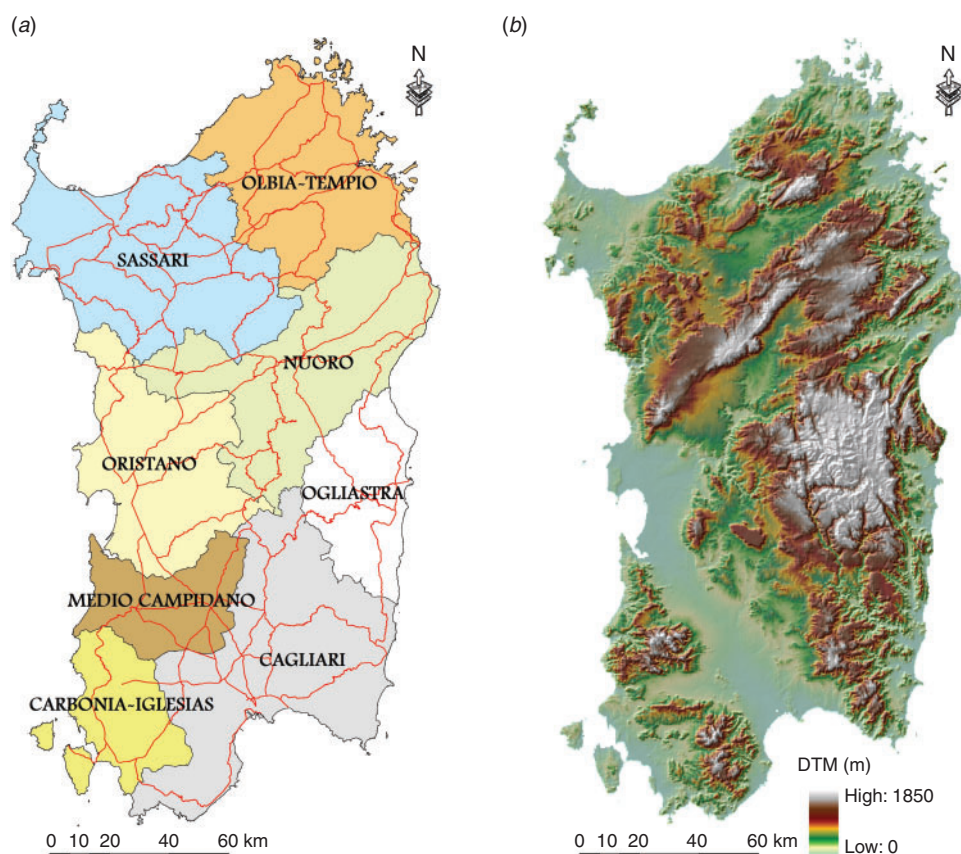


Fig. 2. Maps of Sardinia showing the province boundaries and main roads (a) and elevation (b).

Wildfire history

Wildfires are typically concentrated from June to September, with the peak of ignitions and area burned in July (Fig. 4). During the period 1995–2009, from June to September, Sardinia experienced ~ 2500 fires year⁻¹, with $\sim 17\,000$ ha year⁻¹ of burned area (Sardinia Forest Service, pers. comm. 2010). Approximately 93% of fires burned less than 10 ha, accounting for only 15% of the overall burned area of Sardinia (Fig. 5). The years with large burned areas (1998, 2007, 2009) were associated with droughts, severe heat waves, strong winds and considerable accumulation of fine dead fuel. The accumulation of fine dead fuels is mainly related to high water supply from spring rain promoting growth of herbaceous components in pastures, wooded pastures and Mediterranean maquis, and becoming dead fuel during summer (Baldoni and Giardini 1982; Bullitta *et al.* 1987). By contrast, years with low area burned (1995, 1996, 2006, 2008) were associated with significant precipitation in late May and June, followed by limited drought and the lack of severe heat waves during the whole summer (Sardinia Forest Service 2009). Approximately 90% of the historical fire ignitions were caused by either arson ($\sim 45\%$) or negligence ($\sim 45\%$) (Corpo Forestale dello Stato 2010). Ignition density (Fig. 6) is closely related to proximity to agricultural lands and pastures (Fig. 3) (Bajocco and Ricotta 2008). In specific areas, ignition density has been found to be

also related to the presence of roads, power lines and train tracks (Sardinia Forest Service, pers. comm. 2010).

Input data

We assembled data on fuels and topography in a binary landscape as required by FlamMap (Finney 2006), at 250 m resolution. Elevation, slope and aspect were obtained from 90-m digital elevation data (<http://srtm.csi.cgiar.org/>, accessed 18 September 2012). Surface and canopy fuel were interpreted from the Corine land cover map (EEA 2002) by first stratifying the original 44 classes into 11 fuel types and then assigning either a standard or custom fuel model (Table 1, Fig. 3, Anderson 1982; Scott and Burgan 2005; Arca *et al.* 2009). The custom fuel models were developed as part of earlier wildfire research and were applied to shrubland vegetation (Mediterranean maquis and garrigue) and pastures (Arca *et al.* 2009). Crown bulk density, crown base height and stand height of the wooded areas were estimated using data from the National Inventory of Forests and Forest Carbon Sinks (INFC 2005).

Fuel moisture content (FMC) for the 10-h time lag dead fuel (Table 2) was determined by the methods of Pellizzaro *et al.* (2007) using five seasons of data. The 1-h and 100-h dead FMC and live FMC values (Table 2) were obtained from field observations and literature data (Martins Fernandes 2001; Baeza *et al.* 2002; De Luis *et al.* 2004; Arca *et al.* 2007b; Pellizzaro

et al. 2007). Wind speed and direction data for the fire modelling (Table 2) were derived from Sardinian Forest Service databases and by a set of weather stations (<http://www.tutitempo.net>, accessed 18 September 2012).

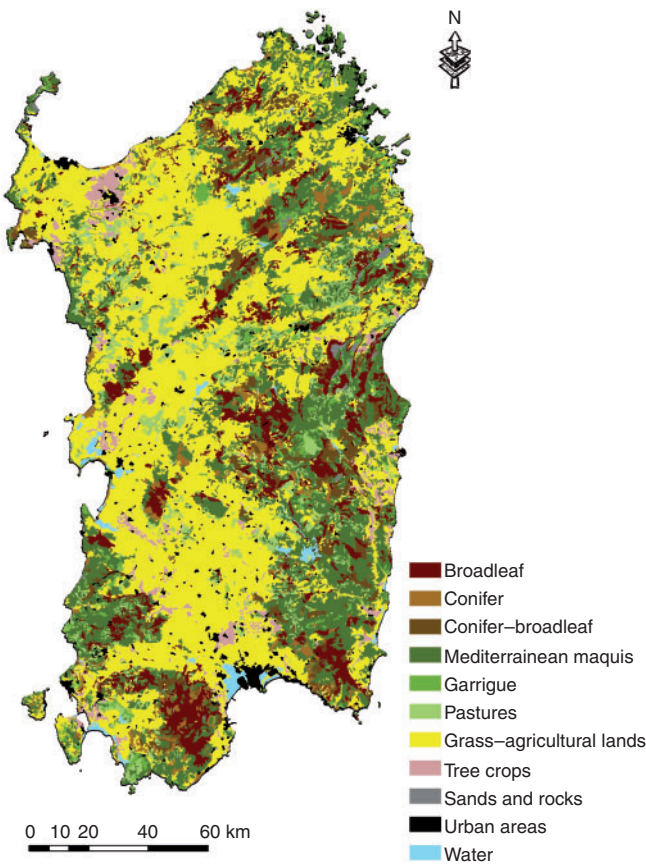


Fig. 3. Map of the vegetation types in Sardinia as derived from Corine land cover data (EEA 2002).

Wildfire simulations

The simulation methods used here were adopted from Ager et al. (2007, 2010a) with refinements as described below. Wildfires were simulated using the minimum travel time (MTT) fire spread algorithm of Finney (2002) as implemented in a command line version of FlamMap called ‘Randig’ (Finney et al. 2006). The MTT algorithm has been extensively described elsewhere and is routinely applied to fire management problems in the US (Andrews 2009; <http://www.fpa.nifc.gov>; http://wfdss.usgs.gov/wfdss/WFDSS_About.shtml, both accessed 18 September 2012). Fire spread is predicted by the equation of Rothermel (1972) and crown fire initiation is evaluated according to Van Wagner (1977) as implemented by Scott and Reinhardt (2001). Randig and FlamMap assume constant wind speed, direction and fuel moisture, and are appropriate for simulating short duration, single-burn-event fires (Ager et al. 2011) like those in Sardinia.

Initial calibration and validation of fuel model assignments and the Rothermel fire spread model as implemented in FARSITE were completed by Arca et al. (2007b) for a set of actual fire perimeters. For the present work, we calibrated Randig by first attempting to replicate the perimeter of a 1200 ha fire in the Olbia-Tempio province (north-east Sardinia) that burned for ~8 h in August 2004. Using fire weather recorded during the fire, we obtained good agreement between actual and simulated fire perimeter (Fig. 7) and average rate of spread (~15 m min⁻¹). Overestimation on the fire flanks was expected and this was observed as they were the focus of fire suppression efforts that were not considered in the simulation. The simulation accuracy of the burned area as measured by the Sorensen coefficient (Legendre and Legendre 1998) was equal to 0.65, and Cohen’s kappa coefficient equalled 0.50, yielding an overall accuracy of 0.77 (Congalton and Green 1999). We next developed simulation parameters that would replicate the distribution of historical (1995–2009) fire sizes. We used weather conditions (wind speed and direction, Table 2) associated with larger escaped fires (97th percentile). Containment activities have minor influence on fire growth during these events. Under these weather conditions,

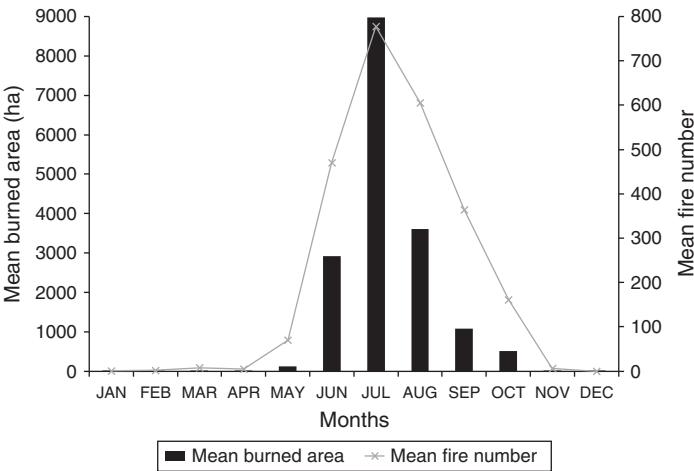


Fig. 4. Monthly fire frequency and size distribution in Sardinia for the period 1995–2009 (data from the Sardinia Forest Service, pers. comm., 2010).

a distribution of burn periods was derived for Randig, which generated a simulated fire size distribution that matched historical records ($n = 523$ large fires, 1995–2009, Fig. 8). We calibrated the fire size distribution with burn periods because the MTT algorithm is not structured to simulate fires of specific sizes, rather fires are simulated under the conditions specified (weather and fuels) until the burn period is achieved. Wind direction was chosen randomly from a frequency distribution developed from the Sardinia firefighter database and observed weather data during escaped fires larger than 100 ha. The largest Sardinian fires typically occur under south-west winds, although the most common wind direction during fires is north-west. Lastly, we built an ignition probability grid (IP) from historic ignition locations using inverse distance weighting (ArcMap Spatial Analyst) with a search distance of 5000 m. The search distance was the minimum value that would generate a nearly continuous map of ignition probabilities for the burnable areas.

Using the above parameters we then simulated 100 000 fire events within the study area, randomly drawing from the frequency distribution of burn periods and wind directions for each fire. The wildfire simulations were performed at 250-m resolution. Randig can locate ignitions either with a probability grid or randomly, and both options were used to assess the effect of ignition location on the outputs. The number of ignitions and the resulting fires were sufficient to generate a cumulative burned area greater than 10 times the study area, and individual pixels were burned on average ~ 12 times. Randig reports a conditional burn probability at each pixel for twenty 0.5-m intervals (0–10 m). The conditional burn probability is the chance that a pixel will burn at a given flame length interval, considering one ignition in the whole study area under the assumed weather conditions. It is defined as:

$$BP_{xy} = \left(\frac{F_{xy}}{n_{xy}} \right) \quad (1)$$

where F_{xy} is the number of times pixel xy burns and n_{xy} is the number of simulated fires (100 000). The conditional burn

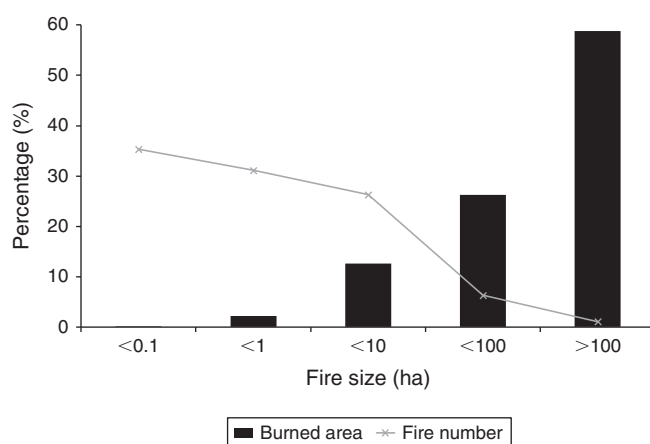


Fig. 5. Historical relationship between fire size categories and percentage of fire number and burned areas in Sardinia, from 1995 to 2009, from June to September (data from the Sardinia Forest Service, pers. comm., 2010).

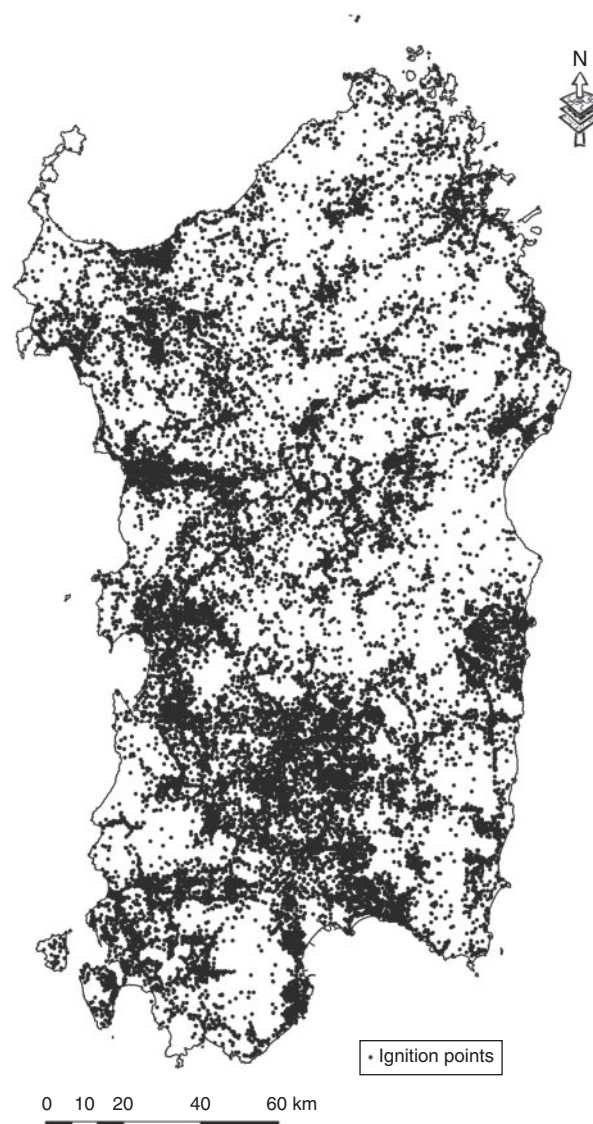


Fig. 6. Spatial distribution of wildfire ignition points for the period 1995–2009, from June to September (data from the Sardinia Forest Service, pers. comm., 2010).

Table 1. Vegetation types and respective fuel models used for the wildfire simulations

Vegetation type	Incidence (%)	Fuel model
Broadleaf	8.9	TL6 (Scott and Burgan 2005)
Conifer	2.8	TL3 (Scott and Burgan 2005)
Broadleaf–conifer mix	3.5	TU1 (Scott and Burgan 2005)
Mediterranean maquis	24.2	CM28 (Arca <i>et al.</i> 2009)
Garrigue	3.2	CM29 (Arca <i>et al.</i> 2009)
Pastures	5.7	CM27 (Arca <i>et al.</i> 2009)
Grass–agricultural lands	44.7	Mod 1 (Anderson 1982)
Tree crops	2.9	Mod 2 (Anderson 1982)
Sands and rocks	0.5	Mod 1 (fuel load reduced 50%)
Urban areas	2.4	NB1 (Scott and Burgan 2005)
Water (lakes, rivers, etc.)	1.2	NB8 (Scott and Burgan 2005)

probability is a relative measure and is useful for comparative risk and exposure analysis (Ager *et al.* 2011).

Fire intensity (Byram 1959) is predicted by the MTT fire spread algorithm and depends on the direction in which the fire encounters a pixel relative to the major direction of spread (i.e. heading, flanking or backing fire), as well as slope and aspect (Finney 2002). Randig converts fireline intensity (FLI, kW m⁻¹) to flame length (FL, m) based on Byram’s (1959) equation (Wilson 1980):

$$FL = 0.0775(FLI)^{0.46}$$

(2)

Table 2. Weather and fuel moisture parameters used in the fire simulations

The values were defined considering the 97th percentile weather conditions and were calculated from Sardinian firefighter databases and weather stations as described in the methods

Variable	Value
Wind speed (km h ⁻¹)	29.0
Temperature (°C)	36.5
Rain (mm)	0
1-h dead FM (%)	7
10-h dead FM (%)	9
100-h dead FM (%)	11
Wind direction (°)	315 (54%)
	225 (24%)
	Other directions (<3%)

The flame length distribution generated from multiple fires burning each pixel was used to calculate the conditional flame length (CFL):

$$CFL = \sum_{i=1}^{20} \left(\frac{BP_i}{BP} \right) (F_i)$$

(3)

where *F_i* is the flame length midpoint of the *i*th category. CFL is the weighted probability of flame length given a fire occurrence,

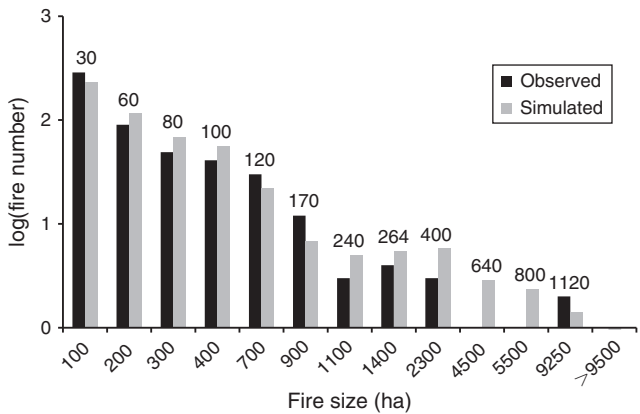


Fig. 8. Log plot of observed and simulated fire sizes and frequencies. The fire size distribution from Randig was obtained using the parameters in Table 2. The burn period (min) used for the simulation of each size category is shown above the bars corresponding to the simulation outputs.

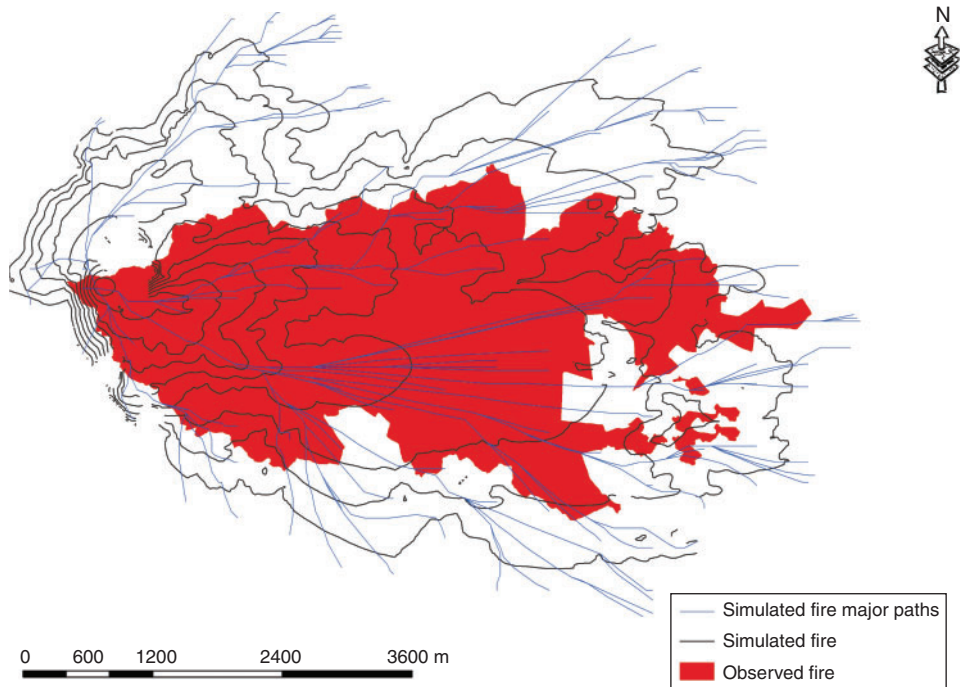


Fig. 7. Comparison between a simulated and actual fire perimeter for the Lu Lioni fire, North East Sardinia, August 2004. The simulation did not model suppression activities (primarily in the south-east and north-west perimeter) and therefore some overestimation of the fire area from the simulation model was expected and observed.

Table 3. Selected landscape features of ecological and economic importance in Sardinia analysed for wildfire risk

Spatial data were obtained from Regione Sardegna (see 1995 data at <http://www.sardegna.territorio.it/webgis/rasscaricocartografia/index>, accessed 24 September 2012), with the exception of vineyards and orchards data, which were obtained from the Corine Land Cover project (EEA 2002)

Feature (abbreviation)	Number of sites or polygons	Average size (ha)	Minimum size (ha)	Maximum size (ha)
Wildland–urban interfaces (WUI)	1120	44.7	0.006	3270.8
Wildlife habitats (WLH)	228	654.2	0.1	7735.2
Parks and wilderness (PRK)	813	300.2	0.1	11 090.4
Vineyards and orchards (VAO)	231	176.9	2.53	5308.9
Dunes and beaches (BCH)	330	40.1	0.1	3072.9
Tourism infrastructures (TOU)	947	–	–	–

and is a measure of wildfire hazard (Ager *et al.* 2007; Ager *et al.* 2010a). Randig also generates text files containing the fire size (FS, ha) and ignition coordinates for each simulated fire. These outputs were used to analyse spatial variation in the size of simulated fires.

We used FS and historical ignition locations to calculate a fire potential index (FPI) as:

$$\text{FPI} = \text{FS} \times \text{IP} \quad (4)$$

where FS is the average fire size for all fires that originated from a given pixel and IP is the historical ignition probability determined from the smoothed map of ignitions (see above). The FPI combines historical ignition probability with simulation outputs on fire size to measure the expected annual area burned for a given pixel. Locations that are characterised by high FPI are likely to have an ignition (e.g. arson) and generate a large fire.

Spatial feature data

We obtained spatial data on selected highly valued features from Regione Sardegna (<http://www.sardegna.territorio.it/webgis/rasscaricocartografia/index>, accessed 18 September 2012) and from Corine Land Cover data (CLC2000, EEA 2002). These features consisted of wildland–urban interfaces (WUI), beaches (BCH), tourism infrastructures (TOU), parks and wilderness (PRK), wildlife habitats (WLH) and vineyards and orchards (VAO, Table 3). To measure wildfire exposure around the urban areas we created a WUI zone that consisted of a 1-km buffer surrounding the urban areas. Whereas a range of buffer distances would have been suitable for the purposes of the study, the 1-km distance was adequate to capture average fire behaviour around urban areas. This distance is not excessively large as to include areas that were not relevant in the context of wildfire exposure of the community. We also created a 1-km buffer around the other highly valued features. The purpose of the buffer was to capture the general fire behaviour in the vicinity of these features so that exposure to values of interest could be measured. BCH data included dune complexes with herbaceous vegetation and low shrubland, and dunes and beaches of tourist interest. PRK included areas that were characterised by wildlands having high physical or biological value, including important forest conservation areas. WLH areas consisted of wildlife preserves, some of which are contained within parks or protected areas. TOU areas included hotels, camping and other tourist facilities.

Results

Burn probability, flame length, fire size and fire potential index

Excluding non-burnable fuels, we obtained a range of burn probability (BP) from 0 to 1.92×10^{-3} , with large spatial variation within the study area (Fig. 9a). As expected, areas of higher BP were concentrated in the western sector of the island and were associated with areas having fuel models characterised by high and very high spread rates, such as grass vegetation. The mean values of BP obtained from simulation using historical ignition locations (6.48×10^{-5}) were similar to those obtained when ignitions were random (6.40×10^{-5}) (Fig. 9a). However, in several patches throughout the island (Fig. 9a, b), especially in the west and south sectors, we observed higher values of BP from historical ignition locations, suggesting that anthropogenic factors strongly affected spatial patterns of BP and also fire behaviour.

Simulation outputs for CFL showed fairly high values for several locations around the island, mostly where fuel models had high load and height (Fig. 10a). In several locations, CFL and BP showed opposite patterns with the highest CFL values located in areas with low BP. The latter trend can be explained by considering that the high fuel loads generally had lower spread rate values, and were mainly concentrated in areas with lower historical probabilities of ignition.

The fire size (FS) analysis revealed areas where ignitions had the potential to generate large fires (Fig. 10b). The simulated FS ranged from 6.25 ha to a maximum of 25 000 ha. Small fires were generated from ignitions near several coastal zones and near areas characterised by fragmented landscapes with a mosaic of vegetation and non-burnable fuels. Large fires were generated when ignitions were located upwind of large fuel fetches that permitted fire spread over long distances, and particularly in some areas characterised by a mix of pastures and shrublands that had fuel models with high predicted spread rates. The areas where simulation outputs predicted large fires generally corresponded to areas where large fires have historically been observed.

The outputs of the FPI (Fig. 10c) showed the most likely locations for large fires. The FPI was calculated as the product of IP and the average FS for each pixel, and measured the potential area burned from ignitions at a given pixel. The outputs showed higher FPI where historic ignitions were high, and where large areas of faster burning fuels were present. These included areas around roads where large areas of pasture and agricultural land were present.

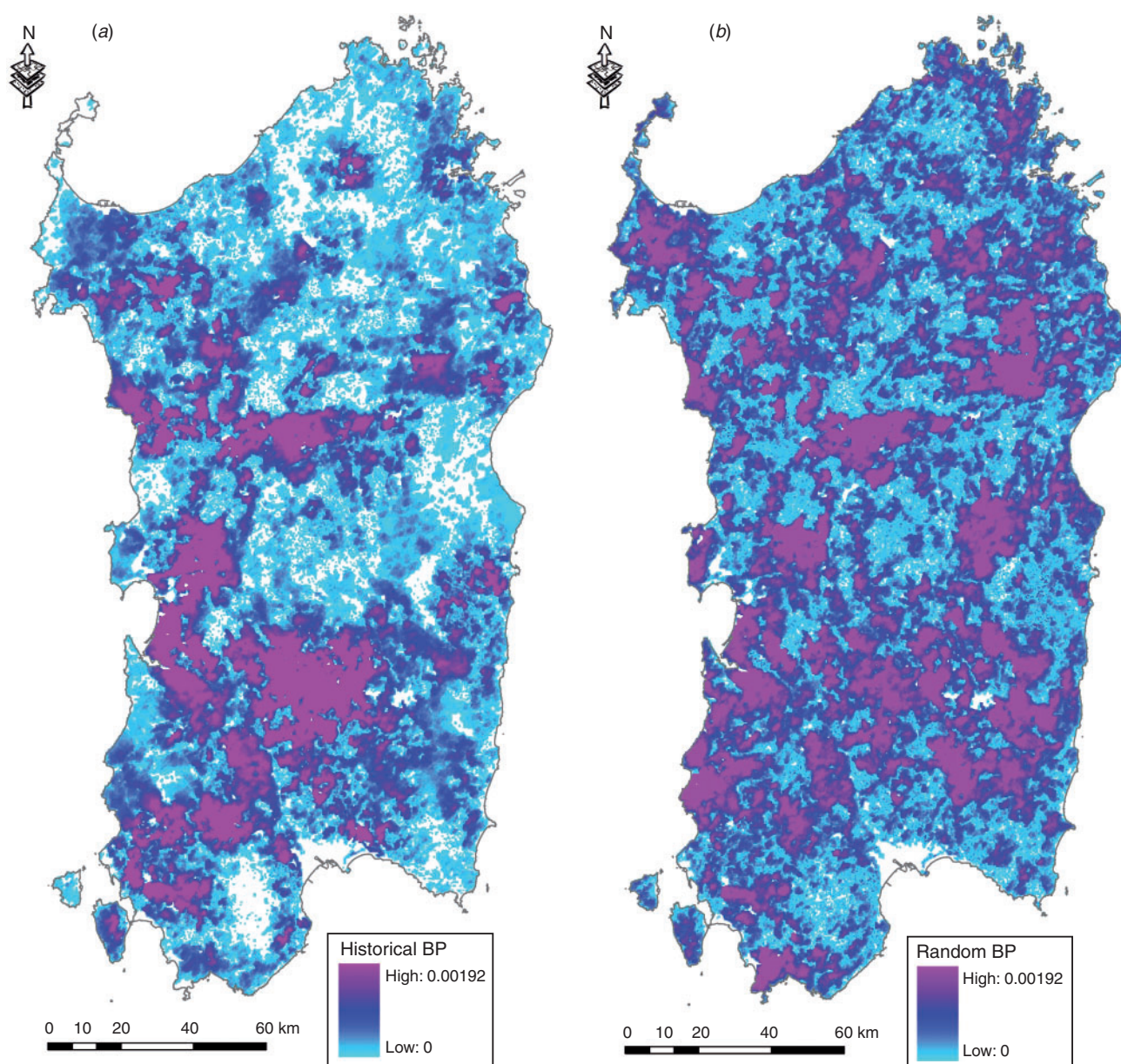


Fig. 9. Burn probability maps with ignition locations sampled from the historical grid (a) and randomly selected (b).

Variation in BP, CFL and FS within and among feature classes

Scatter plots of BP v. CFL and FS for individual polygons of the selected features showed considerable variation of the modelled risk factors in terms of both magnitude and spatial patterns (Tables 3, 4, Figs 11–14). Extreme values of fire exposure for individual polygons were calculated and analysed considering both the mean value and the 95th percentile of BP, CFL and FS for each feature of interest (Table 4, Figs 11–14).

Wildland–urban interface (WUI) areas

Simulation outputs for WUI areas showed fairly high mean values of BP and low values of CFL (Table 4, Figs 11f,

13a, 14f) compared with the other features examined. Several WUI areas had values for both FS and BP above the 95th percentile (Figs 12f, 14f). High values of BP were generally observed in areas that had high historical ignition probability and fuel models with fast spread rates. The north-eastern coasts of the island were characterised by CFL values higher than the 95th percentile, but these severe fires were generally associated with low values of BP (Fig. 14f). The average FS for WUI features was low (Table 4, Fig. 13b); values exceeding the 95th FS percentile were concentrated in the western provinces (Fig. 14f). The average WUI FPI was the second highest among all the features of interest (Table 4), mostly because of the high BP values.

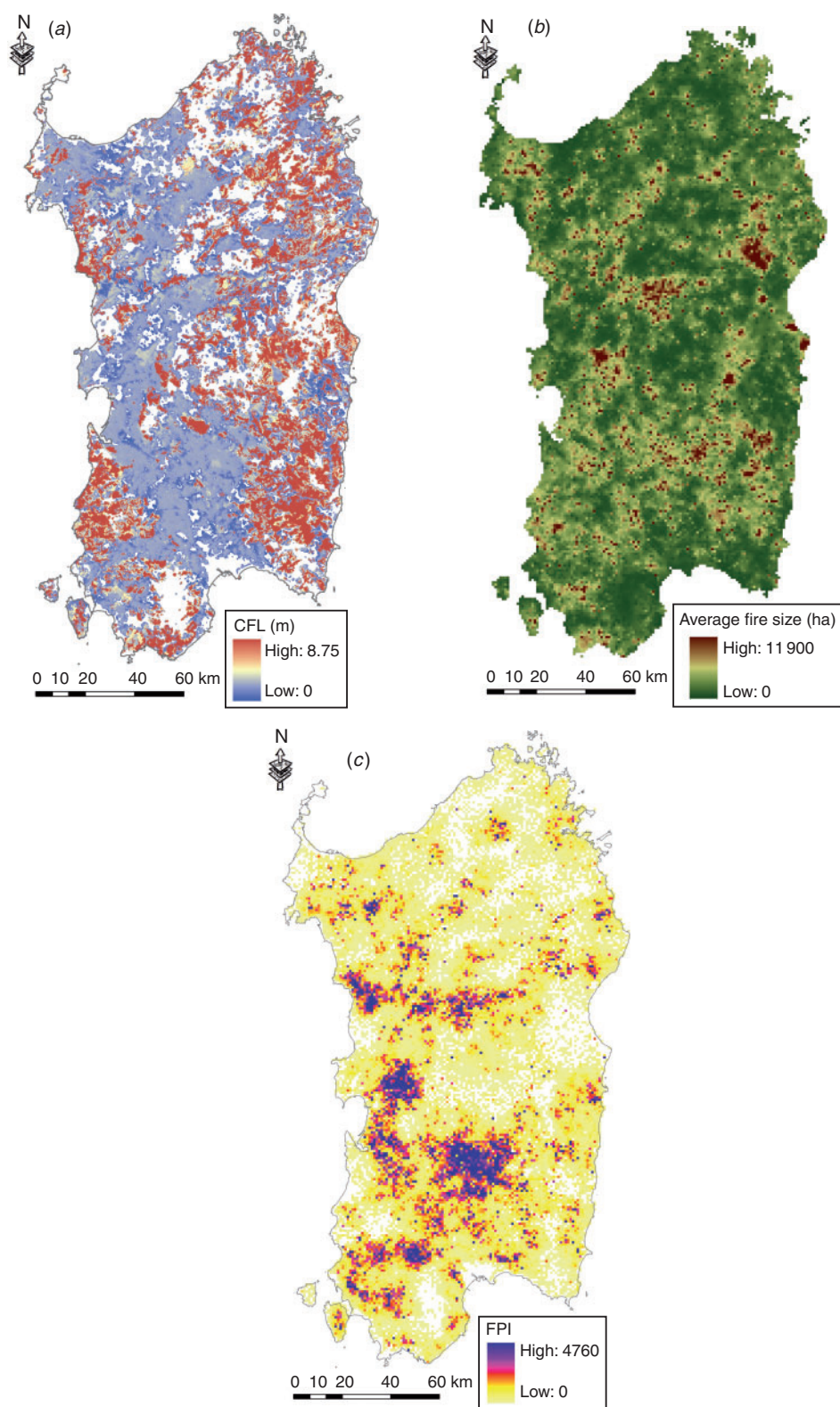


Fig. 10. Maps of simulation outputs for (a) conditional flame length (CFL), (b) average fire size (FS) and (c) fire potential index (FPI), calculated by using the historical grid of ignitions.

Table 4. Mean values and 95th percentile of burn probability (BP), conditional flame length (CFL), fire size (FS) and fire potential index (FPI) for the different highly valued features

Feature (abbreviation)	Average BP	95th percentile BP	Average CFL (m)	95th percentile CFL (m)	Average FS (ha)	95th percentile FS (ha)	Average FPI
Dunes and beaches (BCH)	2.53×10^{-5}	7.61×10^{-5}	1.19	3.21	168.78	315.98	8.16
Wildlife habitats (WLH)	7.64×10^{-5}	2.72×10^{-4}	1.62	3.52	212.25	371.73	16.02
Vineyards and orchards (VAO)	1.71×10^{-4}	5.91×10^{-4}	1.11	2.31	211.58	409.55	35.11
Parks and wilderness (PRK)	6.58×10^{-5}	1.90×10^{-4}	2.13	4.27	232.62	450.15	15.89
Tourism infrastructures (TOU)	4.48×10^{-5}	1.82×10^{-4}	0.94	2.87	161.19	341.35	16.06
Wildland–urban interfaces (WUI)	1.02×10^{-4}	3.57×10^{-4}	1.22	2.99	194.79	368.26	26.48

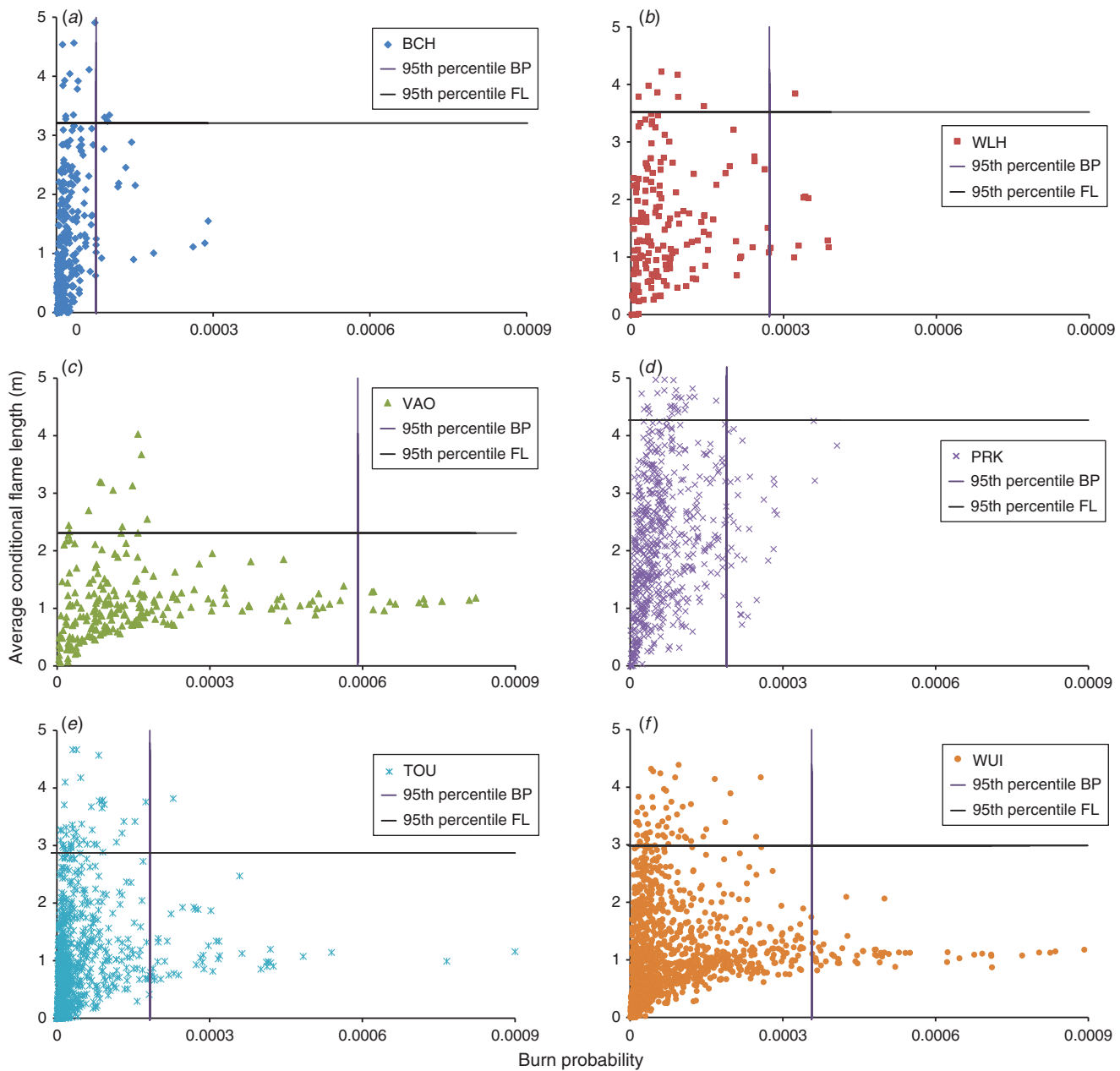


Fig. 11. Scatter plots of burn probability v. conditional flame length for selected ecological and economic values in Sardinia. (a) dunes and beaches (BCH); (b) wildlife habitats (WLH); (c) vineyards and orchards (VAO); (d) parks and wilderness (PRK); (e) tourism infrastructures (TOU); (f) wildland–urban interfaces (WUI). The lines represent the 95th percentile of burn probability (BP) and conditional flame length (CFL).

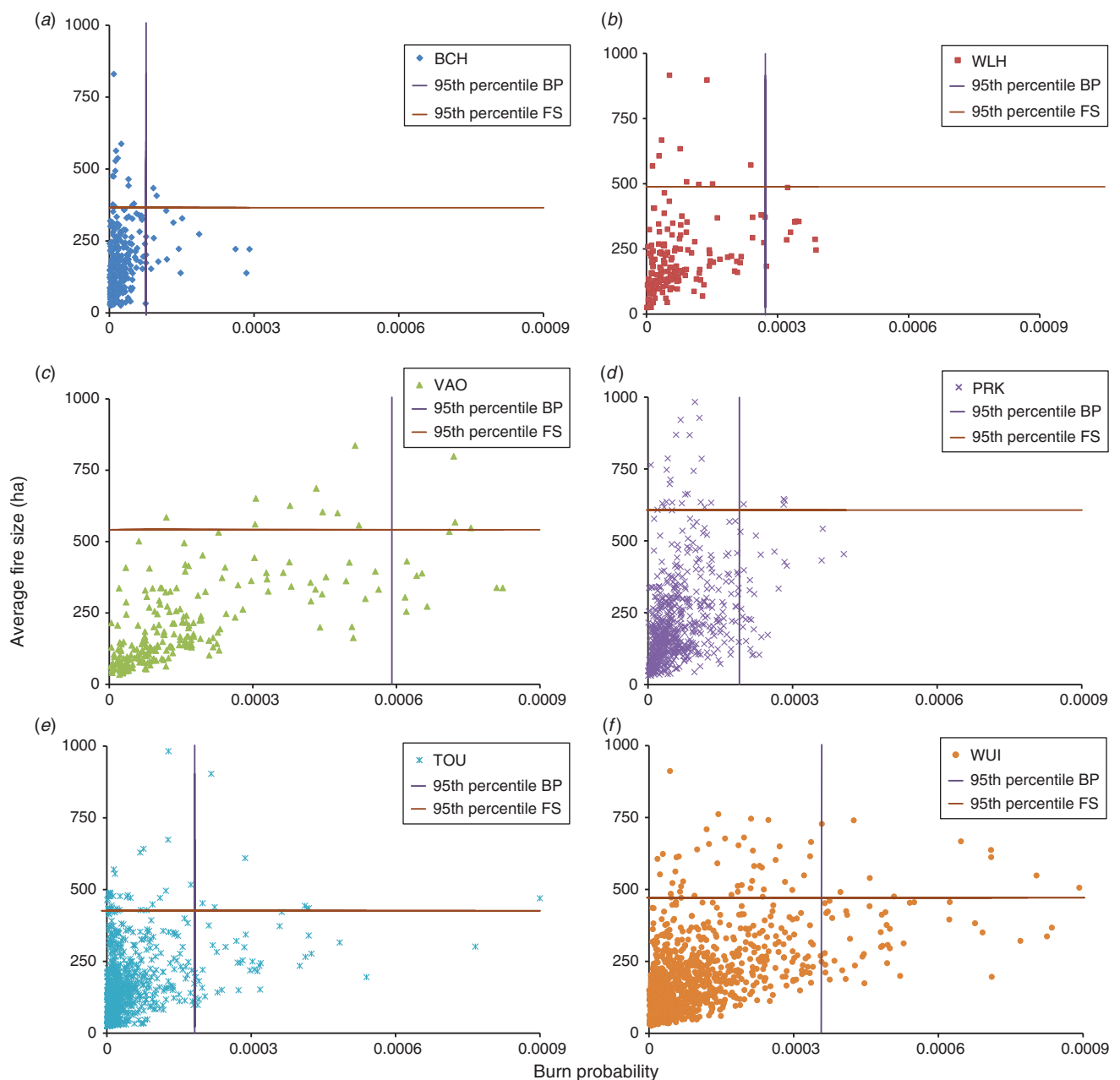


Fig. 12. Scatter plots of burn probability v. fire size for selected ecological and economic values in Sardinia. (a) dunes and beaches (BCH); (b) wildlife habitats (WLH); (c) vineyards and orchards (VAO); (d) parks and wilderness (PRK); (e) tourism infrastructures (TOU); and (f) wildland–urban interfaces (WUI). The lines represent the 95th percentile of burn probability (BP) and fire size (FS).

Parks and wilderness (PRK) areas

The PRK features were characterised by low mean values of BP, mostly due to low ignition probability (Table 4, Figs 11d, 13a, 14d). This result could be related to the prevention actions of the Sardinia Forest Service. Although the mean values and the 95th percentiles for FS and CFL were high (Table 4, Figs 11d, 12d), none of the PRK features had a combined value above the 95th percentile threshold (Figs 11d, 12d, 14d). CFL values higher than the 95th percentile (4.27 m, Table 4) were observed on small areas of the eastern flank of the island where PRK

buffers were characterised by fuels with high loading (Fig. 14d). The average FPI for this feature was low compared with the other features (Table 4).

Dune and beach (BCH) areas

BCH areas had the lowest average BP and FPI among all features analysed (Table 4, Figs 11a, 12a, 13a) and plots of the three risk factors did not highlight areas with combined values above the 95th percentile threshold (Figs 11a, 12a). The analysis of the spatial patterns showed that ~50% of the areas that

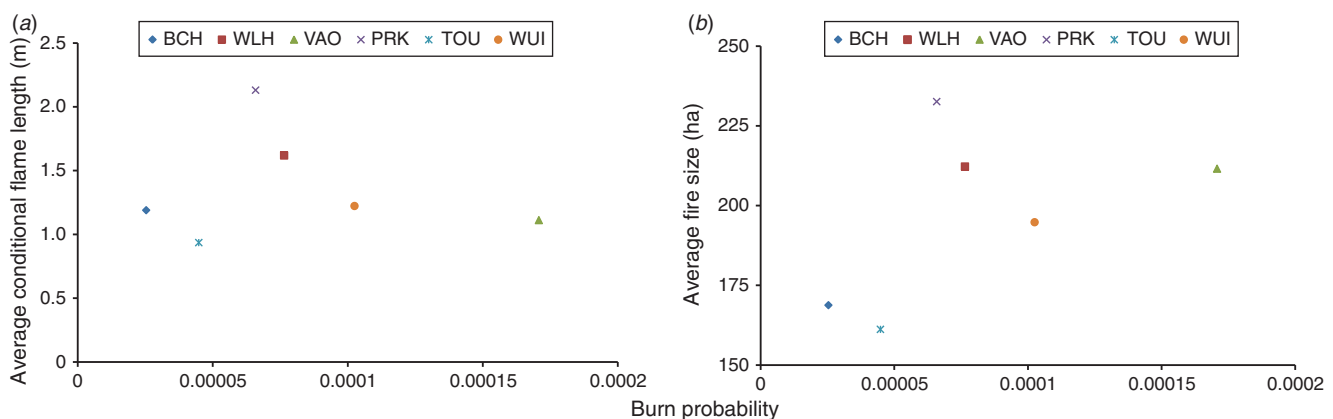


Fig. 13. Scatter plots of overall average burn probability *v.* conditional flame length (a) and burn probability *v.* fire size (b) for selected ecological and economic values in Sardinia. Values plotted are the mean of all polygons for each of the features.

exceeded the 95th BP percentile were located on the south-western coasts, whereas the highest CFL values were mainly concentrated on the north and north-eastern coasts (Fig. 14a) where low values of BP were observed. This can be explained by the presence of non-burnable fuels near BCH, the fragmentation of the land uses due to the concentration of human activities and the short distance between BCH buffer areas and the coastline. On the other hand, CFL values for some areas were very high, meaning that fires were of high intensity and therefore potentially dangerous for people. These results are consistent with severe fire behaviours observed in shrubland areas located in the north-eastern coast that required, in many cases, complex fire-fighting and management activities (Sardinia Forest Service, pers. comm.). Ignitions for simulated fires around the BCH areas generated small fires (Table 4, Figs 13b, 14a).

Tourism infrastructure (TOU) areas

Overall, the fire simulation outputs showed low values for the risk factors within TOU areas compared with the other features studied (Table 4, Figs 11e, 12e, 13a, 13b, 14e). TOU areas were characterised by a low average BP (Table 4). The areas with BP values exceeding the 95th percentile were distributed uniformly around the island (Fig. 14e). The average CFL and FS for the TOU areas were the lowest among all features (Table 4, Fig. 13a, b), indicating little potential for high intensity fires. This can be explained by the fragmentation of fuels in these areas and the presence of residential or non-burnable fuels (beaches, humid areas, rocks, etc.), as already observed in the BCH areas. CFL values higher than the 95th percentile were observed on the north-eastern coasts of the island, where TOU infrastructures are mainly concentrated (Fig. 14e).

Vineyards and orchards (VAO) areas

The highest average BP among all features analysed was observed for VAO areas (Table 4, Fig. 13a, b); the highest BP values were located in the agricultural plains on the western side of the island (Fig. 14c). VAO were characterised by a large number of fires that exceeded several thousand hectares, contributing to high average FS and 95th percentile FS values

(Figs 12c, 13b). Areas near VAO can therefore be considered as important fire sources. The large fires associated with this feature were the result of extensive areas of herbaceous vegetation that had high predicted fire spread rates at low intensities.

Wildlife habitat (WLH) areas

BP and CFL within WLH showed a large range of values, although limited variability was observed for FS (Table 4, Figs 11b, 12b). More than 60% of the WLH areas that exceeded the 95th percentile in BP were located on the western side and the central-southern part of the island (Fig. 14b). The highest CFL values (Table 4, Figs 13a, 14b) were observed in the northern part of Sardinia. Fires with FS exceeding the 95th percentile were concentrated in two WLH areas located in north-eastern and southern Sardinia (Fig. 14b). The highest FPI values for wildlife habitats were recorded in the central southern area (Table 4).

Discussion and conclusions

The main goal of this paper was to analyse wildfire exposure of key ecological, social and economic features from large fire events in Sardinia. The study represents the first application of burn probability modelling to capture landscape scale risk and exposure factors (BP, CFL, FS, FPI) in the Mediterranean region. Many other risk and exposure studies have been reported for other fire-prone systems including the US, Portugal, Spain, Greece, Israel, Australia, New Zealand and India (Preisler *et al.* 2004; Iliadis 2005; Loboda and Csiszar 2007; Kalabokidis *et al.* 2007; Vasilakos *et al.* 2007; Vilar del Hoyo *et al.* 2008; Carmel *et al.* 2009; Catry *et al.* 2009; Martínez *et al.* 2009, Atkinson *et al.* 2010; Braun *et al.* 2010; Chuvieco *et al.* 2010; Keane *et al.* 2010; Verde and Zezere 2010; Thompson *et al.* 2011). However, with the exception of a few studies in the US, most other studies focus on localised parameters (ignition location and hazard) rather than identifying spread patterns of large fires and the resulting transmission of risk across the landscape.

As with any wildfire simulation effort there are many sources of uncertainty in the model and the results should be viewed as general indicators of relative wildfire exposure for features

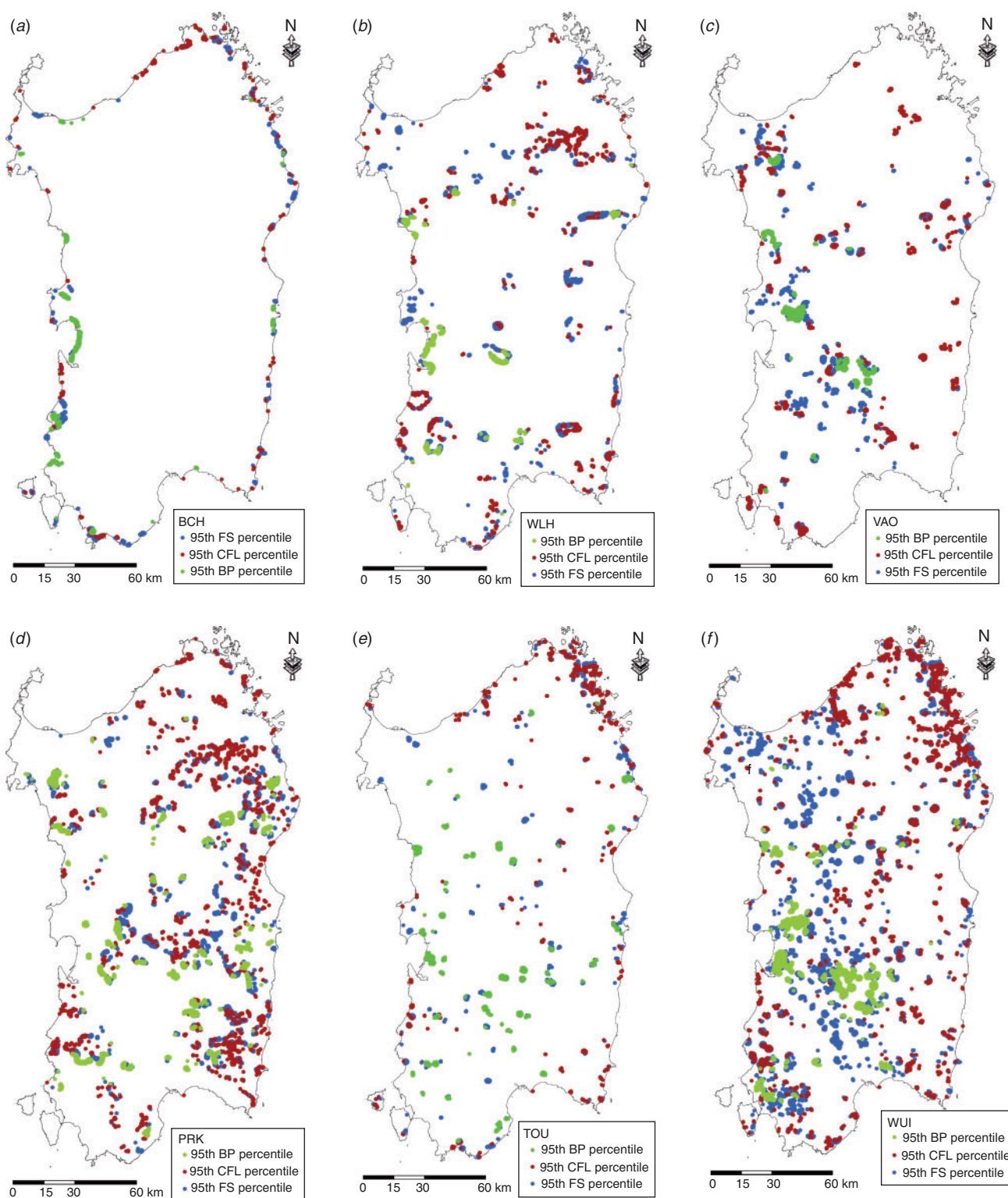


Fig. 14. Maps of pixels with higher than 95th percentile values of burn probability (BP), conditional flame length (CFL) and fire size (FS) for (a) dunes and beaches (BCH); (b) wildlife habitats (WLH); (c) vineyards and orchards (VAO); (d) parks and wilderness (PRK); (e) tourism infrastructures (TOU); (f) wildland-urban interfaces (WUI).

examined. Ongoing research on fuel characteristics and fire behaviour in Sardinia will help refine simulation parameters and improve maps of exposure and risk. The methods can be potentially applied throughout the Mediterranean region using the Corine land cover map and careful calibration of the fire behaviour models.

The analyses suggested marked spatial variation in exposure of important features to wildfire on the Sardinian landscape. This finding has direct application for prioritising fuel management and fire protection efforts. The outputs provide a quantitative assessment of wildfire exposure at the landscape scale, as compared with works that relied on discrete or qualitative indices. Furthermore, by simulating fire events, we captured landscape properties of wildfire exposure that are not considered in indices developed primarily from ignition maps. We also created a new index that combines the empirical ignition probability with the simulated fire size (FPI, fire potential index) to map the expected area burned from specific ignition locations. This index can help guide arson mitigation efforts by identifying where these activities are most likely to occur and cause most damage. In terms of specific findings, the maps and graphs can be used to begin communicating wildfire risk to specific landowners and communities in Sardinia, and to target specific areas for additional fuel management and protection efforts. Refinement of the modelling methods and data will continue while the current results are integrated into fire management planning by the Sardinian Forest Service. This work in particular demonstrates the relevance of investing in fuel mapping and research to calibrate fire behaviour models (Arca *et al.* 2007b; Arca *et al.* 2009).

It is important to note the difference between the conditional burn probability used in this study *v.* empirical estimates of wildfire likelihood derived from historical data. The latter can be calculated for the study area as the proportional area burned by all fires per year, and estimates the average probability of a point burning within the study area. The value for Sardinia for the period 1995–2009 is 7.10×10^{-3} , which is comparable to other Mediterranean regions like Corsica (5.50×10^{-3}) and Sicily ($\sim 6.00 \times 10^{-3}$). However, these empirical estimates are too coarse to be useful for spatially explicit assessments of wildfire risk and exposure, and to inform local risk mitigation strategies for individual land owners and communities. The BP estimates from our simulations overcome these limitations, although they provide relative *v.* absolute measures of wildfire likelihood.

We used empirical data on ignition location to build an ignition probability grid for the wildfire simulations, and examined random ignitions as well. The use of an ignition probability grid had a substantial effect on the spatial patterns of BP, and resulted in localised areas of elevated BP around sites with high ignition frequencies. Incorporating historical ignition patterns is important for describing burn probability in systems where fires are human caused (Syphard *et al.* 2007; Bar Massada *et al.* 2011), but is less important in areas like the western US where large, lightning-ignited fires spread to locations distant from the ignition point (Finney *et al.* 2011).

Substantial variation was observed both within and among the features examined for all of the risk factors and this provides a clear basis to identify individual features that are most exposed

to one or more wildfire risk factors. The variation resulted in a strong effect of fuel models coupled with weather and topography. In particular, the combined effect of Mediterranean maquis, woodland areas and complex topography on CFL was relevant, mainly in the north-eastern areas of Sardinia, whereas areas with herbaceous fuel were in general characterised by lower CFL but higher BP.

The relative values of the risk factors (BP, CFL and FPI) can be used to guide the development of specific risk management strategies. Among the features studied, as shown in Fig. 13, vineyard and orchard areas had the highest BP and high FS values, together with the lowest values of CFL. High intensity fires were more common in parks and wilderness that showed an intermediate average BP coupled with the highest values of CFL and FS. Although these areas were historically characterised by a low number of fire ignitions due to prevention and protection activities, the high exposure to severe and large fires seen in the simulations highlights the need for strategic fuelbreaks to facilitate fire prevention activities. The high values of CFL and FS in parks and wilderness can be related to the general presence of fairly high fuel loadings associated with the Mediterranean maquis and forests (Arca *et al.* 2009). A similar pattern in terms of CFL was seen in wildlife habitats, although these areas were characterised by lower values of FS and very low values of BP. The analysis on tourism infrastructures did not show relevant fire risk issues for most of the areas, in particular in terms of FS and CFL. For the WUI features, we observed high values (greater than the 95th percentile) of BP and CFL for specific communities, which suggest elevated wildfire exposure and the need to identify specific areas for fuel management and evacuation plans to reduce human exposure to wildfires. The results also identify specific Sardinian beaches, which are the target of frequent arson fires that have caused numerous injuries and fatalities in recent years, as having high wildfire exposure.

Burn probability modelling offers more robust measures of wildfire likelihood compared with methods employed previously, where fire likelihood was quantified with few predetermined ignition locations (LaCroix *et al.* 2006; Loureiro *et al.* 2006; Duguay *et al.* 2007; Ryu *et al.* 2007; Schmidt *et al.* 2008). The development of the MTT algorithm in Randig and the implementation in FlamMap and other wildfire simulation systems make it possible to map and analyse fire risk exposure, eliminating potential bias from assuming a small number of specific ignition locations. This modelling approach can also be used to investigate several issues such as the potential effects of climate change, land use change, vegetation succession and fuel management programs. In addition, analyses of effects of wildfire on factors such as soil erosion (Robichaud *et al.* 2009) or carbon cycling (Ager *et al.* 2010b) can be quantified with a probabilistic framework (e.g. expected loss) to account for the uncertainty in wildfire occurrence and intensity. For instance, post-fire erosion is of great concern in some areas of Sardinia (Vacca *et al.* 2000; Canu *et al.* 2009) and soil erosion models can be coupled with these simulation outputs to generate estimates of expected effects of erosion that account for stochastic variation in fire occurrence and intensity.

Locally, the Sardinia Forest Service and municipalities can use the information obtained in this study for a range of purposes. The FPI index might guide fire education programs

to reduce accidental ignitions, which in the United States has shown to be an effective means of reducing wildfire incidence (Prestemon *et al.* 2010). Expansion of this approach to other areas of the Mediterranean Basin is underway, and requires the association of the Corine Land Cover map to fuel models and fuel moisture files, the refinement of fuel model maps and input parameters and the analysis of the historical fire regimes. In particular, work is in progress to perform wildfire simulations and risk analysis for other Sardinia neighbouring areas. Further calibration and implementation could allow the development of burn probability and fire risk models at regional scales that may support large-scale climate change analyses and may address other regional wildfire risk issues. Additional case studies with the Corine land cover maps on fire prone regions in Europe are needed to refine existing, and develop new methods for deriving fuels maps for the expanded application of wildfire risk modelling.

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