Special Issue Paper

Environmetrics

Received: 6 September 2013, Revised: 8 January 2014, Accepted: 7 February 2014, Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI: 10.1002/env.2269

Wildfire risk estimation in the Mediterranean area

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We analyzed wildland fire occurrence and size data from Sardinia, Italy, and Corsica, France, to examine spatiotemporal patterns of fire occurrence in relation to weather, land use, anthropogenic features, and time of year. Fires on these islands are largely human caused and can be attributed to negligence, agro-pastoral land use, and arson. Of particular interest was the predictive value of a fire weather index (FWI) that is widely used by fire managers to alert suppression crews. We found that an increase in the FWI from 30 to 60 produced on average an approximate eightfold increase in the odds of a large fire, regardless of the time of year during the fire season or land use type. Total area burned per fire season was positively correlated with the number of days with FWI > 40 over the period studied. Strong interactions between time of year and land type were also observed for both the probability of ignition and large fire. For example, the estimated odds of a large fire on agricultural lands in southern Sardinia was approximately 10 times larger than the forest and shrubland land type for areas close to roads, early (May) in the fire season. Conversely, toward the end of the fire season (September), we estimated the odds of a large fire in these same areas at about half the value estimated for the forest land classes. Of the explanatory variables analyzed, only FWI had an effect on the probability of a large fire (*P* < 0.1). The results of the study can be used in several ways including the following: (1) allocating fire detection and suppression resources to specific locations during the fire season; (2) prioritizing fuel breaks along specific road segments that have high predicted ignition rates; (3) refining the current fire danger indices; and (4) parameterizing wildfire simulation models to test how changing land use and climate change may affect spatial patterns in burn probability and intensity.

Keywords: Sardinia wildfire; Corsica wildfire; fire weather index; generalized additive model; generalized Pareto distribution

1. INTRODUCTION

Wildfires pose a substantial threat to human and ecological values in the fire-prone areas of the Mediterranean Basin, where extreme fire seasons are common and cause substantial human and ecological losses (Mouillot and Field, 2005; Trigo *et al*., 2006; Viegas, 2006; Xanthopoulous, 2007; Riaño *et al*., 2007; Moreira *et al*., 2011; Salis *et al*., 2013b). During the period 2000–2009, countries of southwestern Europe (Italy, France, Spain, Portugal, and Greece) experienced about 57,000 wildfires annually, burning 430,000 ha (JRC-IES, 2010). It is estimated that more than 90% of fires were caused by arson, negligence, and agro-pastoral land burning (MMA, 2007; Corpo Forestale dello Stato, 2010; Salis *et al*., 2013a). The wildfire problem is generally expected to increase in the future in response to predicted changes in climate and land use (Moriondo *et al*., 2006; IPCC, 2007; Arca *et al*., 2010). A number of empirical studies have been conducted in the region to better understand the spatiotemporal patterns of wildfire ignition and build predictive models to use in wildfire danger and risk systems (Chuvieco *et al*., 2003, Martínez *et al*., 2009; Carmel *et al*., 2009; 2010; Verde and Zezere, 2010). These studies have found strong relationships between wildfire occurrence and explanatory variables such as roads, land use, fuel, and weather. However, untangling the interrelationships among the explanatory variables in space and time is complicated, owing to the multiple drivers of fire ignition probability and subsequent fire spread, and thus, researchers have generally limited their investigations to relatively few explanatory variables to simplify the problem. For instance, studies in Sardinia have focused on broad spatial patterns related to land-type polygons and associated fuel phenology, leaving out potential effects from anthropomorphic features such as roads and population density in the models (Bajocco *et al*., 2010). Another gap in fire management research in the region is that some of the fire danger indices have not been closely examined for their ability to explain past spatiotemporal patterns of wildfire, and thus, their validity has not been established, especially at local scales.

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In this paper, we analyze historical fire occurrence and size data in Sardinia and Corsica using nonparametric statistical models to understand the interactive effects of anthropogenic and weather variables on fire occurrence and size. The results are discussed in the context of mapping wildfire risk and danger for fire detection and prioritizing fuel treatment projects.

2. DATA

2.1. Study areas

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 (Figure 1). Sardinia is divided into eight provinces and has about 1.7 million inhabitants, mostly concentrated in the provinces of Cagliari and Sassari. The island orography consists of rolling hills and small mountains (Figure 1(A)), with the highest point being 1850 m above sea level in the center of the island. The climate consists of mild, rainy winters, dry, hot summers, and a substantial water deficit from May until September (Chessa and Delitala, 1997). The water deficit generally increases from north to south and from mountainous areas to plains. The annual precipitation ranges from a low of 500 mm on the southern coastlines to a high of 1300 mm in the mountains. The mean annual temperature follows a similar trend with a low of 12 °C in the mountains and a high of 17 °C along the southern coast.

Sardinia experiences an average of 2219 fires per year based on data from 1995 to 2009 with fires averaging 7 ha in size. On average, an area of 16,601 ha burns per year, with the largest fire reaching a size of 9029 ha. Fires greater than 50 ha are relatively rare and represent 1.8% of all fires (about 40 per year) but account for 68.7% of the total annual area burned.

Corsica, France, is the fourth largest island in the Mediterranean and is located in the northwestern part of the Mediterranean Basin, between 41°00′–43°00′N latitude and 8°00′–10°00′E longitude (Figure 1); Corsica covers about 9000 km^2 with 0.3 million inhabitants. The orography is highly variable, with several mountain ranges in the interior of the island, and with rolling hills and plains near the coast. The climate is similar to Sardinia with cool, moist winters and hot, dry summers. Corsica experiences fewer fires than Sardinia, averaging 536 fires per year based on data from 1995 to 2009, with a mean fire size of 7.9 ha. The maximum fire size during the period examined was 5532 ha, and on average, 4731 ha burn per year. As in Sardinia, fires greater than 50 ha are rare (about 10 per year) and account for 1.9% of all fires and 98.6% of the total annual area burned.

2.2. Vegetation

In Sardinia, woodlands and forest are approximately 16% of the vegetated area and are mainly comprised of *Quercus ilex* L., *Quercus suber* L., and *Quercus pubescens* Willd. At higher elevations, the oak formation merges with *Castanea sativa* Mill. and *Ilex aquifolium* L. The coniferous stands (*Pinus* spp.) are limited (3%). Mediterranean maquis and garrigue covers 28% of the island. Urban and anthropic areas cover about 3% of the landscape. The remaining fractions are pasture and agricultural land types (49%) and other land uses (Figure 1(B), EEA, 2002).

The vegetation of Corsica is mostly characterized by Mediterranean maquis and garrigue, which constitutes 43% of the vegetation. Broadleaf forest occupies another 20% (*Quercus ilex* L., *Quercus suber* L., and *Quercus pubescens* Willd). In the interior mountains, oaks are replaced by

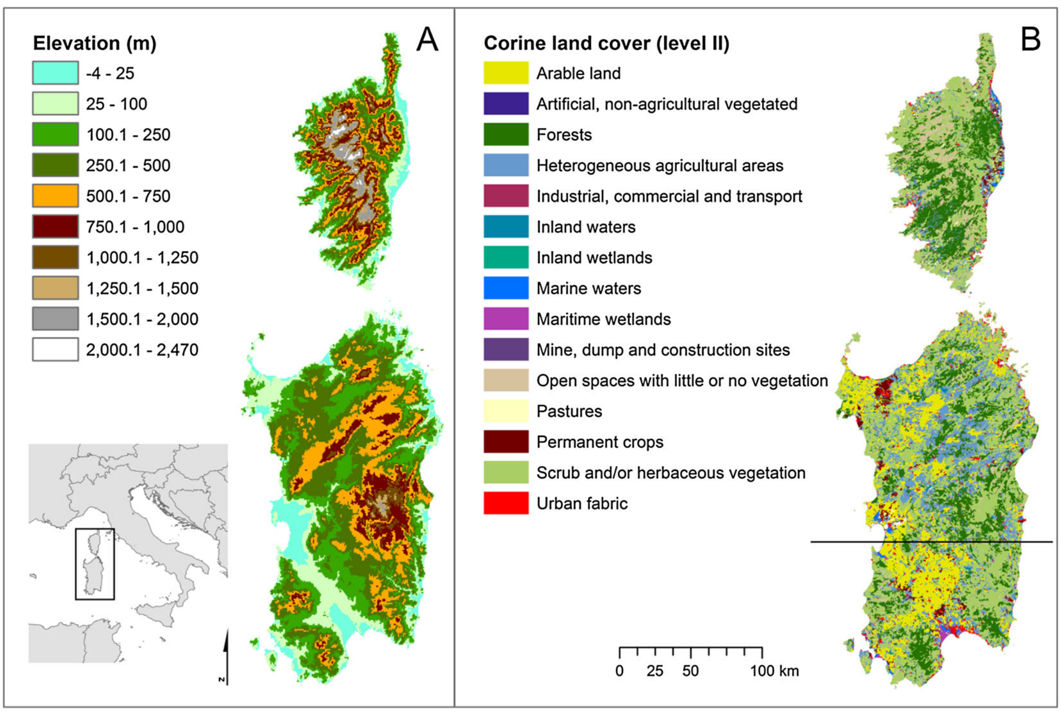

Figure 1. Map of Sardinia and Corsica showing (A) elevation and (B) major vegetation types (Corine land cover level II, EEA, 2002). Black line bisecting Sardinia marks the boundary between the northern and southern agricultural regions used in the analysis. Note that the level III Corine classification, which is too fine scaled to display in the figures, was used for the present study

other broadleaf deciduous trees (*Castanea sativa* Mill.). The coniferous stands are primarily *Pinus nigra* Arnold and *Pinus pinaster* Aiton and cover approximately 5% of the island. Agricultural and herbaceous areas (23%) are quite limited relative to Sardinia. Urban and anthropic areas cover about 2% of Corsica (Figure 1(B), EEA, 2002).

2.3. Wildfire occurrence data

The Sardinian Forest Service began recording fire ignitions in a standardized database in 1980 (Corpo Forestale e di Vigilanza Ambientale, personal communication). The database includes data on the ignition date, municipality, area burned (ha), and ignition location. For a portion of the records (<50%), the database also contains an assessment on the probable cause of the ignition, although these notations lack formal investigations or validation and are only useful for coarse summaries at best. Ignitions are recorded using the same process regardless of the individual fire characteristics (e.g., location or size). The ignition locations and fire perimeters have been determined with GPS since 2003, and our assessment of the accuracy of the database indicated that the locations are recorded with less than 200 m error. We encountered a small number of records (<2%) where coordinates were missing and ignitions had to been assigned a random coordinate within the reported municipality.

For Corsica, we obtained ignitions from similar standardized databases maintained in France (Prométhée, 2013). In these data, fire locations are recorded to the nearest centroid of a national 80-ha grid (894 x 894 m). The resulting error thus ranges from 0 to 447 m, with an average of ~223.5 m, assuming fires are located randomly within each 80-ha parcel.

2.4. Explanatory variables

Daily data on temperature, wind speed, relative humidity, and precipitation were obtained for 11 weather stations for Sardinia and five for Corsica (TuTiempo.net, 2013). For temperature and wind speed, the data included daily minimum, maximum, and average values. Each weather station was assigned to one of four regions (north and south Sardinia and north and south Corsica), and average daily values were then calculated for each region. The merging of the weather stations into regions was required to fill gaps in the weather records over the period studied. We used the weather data to calculate the Fire Weather Index (FWI, Van Wagner, 1967) for each day and region and assigned this value to each ignition in the fire history database. Although we were interested in analyzing other fire danger indices used in the study area, such as the Ichnusa Fire Danger Index (IFI, Sirca *et al*., 2006) and an empirical fire danger model developed by the Sardinian Forest Service (Regione Autonoma della Sardegna, 2011, p. 37), the lack of spatiotemporal data for the study area precluded these investigations.

We used the Corine land cover data (CLC, EEA, 2002, 2012) to analyze ignition probability in relation to land use patterns and vegetation types. The CLC data are a seamless vector coverage of land cover for Europe mapped at a scale of 1:100,000, with a minimum mapping unit of 25 ha and a minimum width for linear elements of 100 m. The coverage was generated by the European Environment Agency from IMAGE2000 satellite imagery. The CLC classification includes 44 land cover classes, grouped in a three-level hierarchy, with level 1 being the coarsest and level 3 the finest (see Figure 1(B) for level 2 maps). Each ignition location was assigned to a land type based on its location in the Corine coverage.

We obtained slope (degrees), aspect (degrees), elevation (m), location of roads, location of communities, and number of inhabitants within communities from the Sardinian Geo-Portal (Geografia Della Sardegna, 2013). For Corsica, we obtained these data from a digital data library from CGIAR CSI (2012). Road locations and number of inhabitants for communities for Corsica were obtained from the Corsican Forest Service data library.

We calculated the distance (m) between each ignition and the nearest road and community using the NEAR function in ArcMAP and then attributed the ignition with the resulting value. Ignitions located within community boundaries were assigned the number of inhabitants within the community.

3. EXPLORATORY ANALYSIS OF FIRE IGNITIONS

In Sardinia, more than 90% of the historical fire ignitions were caused by either arson (~45%) or negligence (~45%) (Corpo Forestale dello Stato, 2010; Salis *et al*., 2013a). In Corsica, about 90% of the historical fire ignitions were caused by either arson (~32% in the south and ~66% in the north) or negligence (~62% in the south and ~33% in the north) (Prométhée, 2013). Wildfire activity in terms of number of ignitions and area burned per fire peaked in July for both islands (Figure 2). Maps of spatial patterns of large fires (>50 ha), and their relationship to FWI, showed that large fires had strong spatial clustering, with concentrations of fires in the southern portion and, to a lesser extent, the central region of Sardinia (Figure 3(A, B)). Comparing large-fire occurrence with a smoothed map of FWI (Figure 3(C)) clearly shows a lack of coincidence, which is especially apparent in the two locations with the highest frequency of large fires—the southern and central regions of Sardinia. The two maps show that broad indicators of fire danger like the FWI, averaged over time, can only partially explain fire occurrence.

Mapping ignition data at finer scales revealed strong spatial patterns in relation to both roads and time of year (Figure 4). The clustering around roads shown in Figure 4 was observed throughout the study area, although substantial variation in the timing of the ignitions within the fire season was apparent, with some road segments having the bulk of the ignitions early in the fire season (June) versus others that had ignitions later (August). What is not clear from the maps is the cause for the seasonal effects, whether it is the behavior of arsonists, annual crop cultivation, or agro-pastoral field burning. The Forest Service in Sardinia has reported that some arsonists repeatedly ignite fires in the same locations based on previous success at generating large fires. However, farmers and shepherds might also use the same ignition location to burn fields as part of their land use practices.

To gain insight on the relationship between land use patterns and the timing of ignitions, we examined monthly ignitions by CLC type (Figure 5). Substantial variation among the land types was observed in the ignition density and percentage of area burned of each land type (Figure 5(A)). With few exceptions, the discontinuous urban fabric land and complex cultivation types had the highest ignition frequency and percentage of area burned. Ignition density was relatively stable over the fire season, compared with the percentage of area burned, which declined from a peak during July, followed by June, August, and September, and thus, average fire size changed over the fire season. Both natural grasslands and agroforestry areas had relatively low ignition frequency and large area burned compared with the other land types,

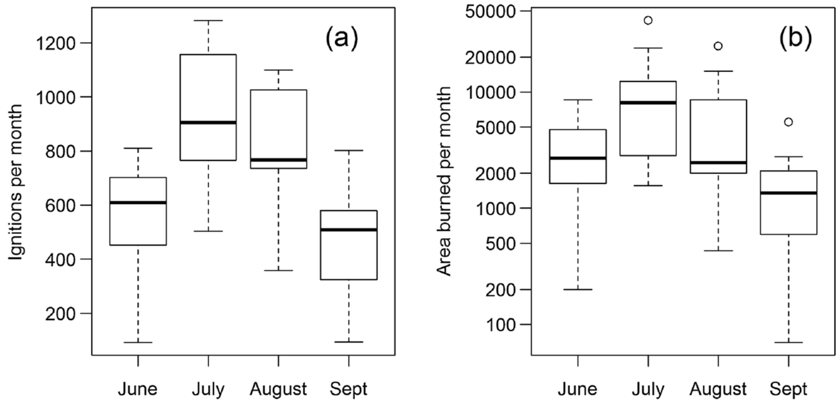

Figure 2. Box plots of fire occurrence data from Corsica and Sardinia showing monthly variation in (a) ignition frequency and (b) total area burned (ha)

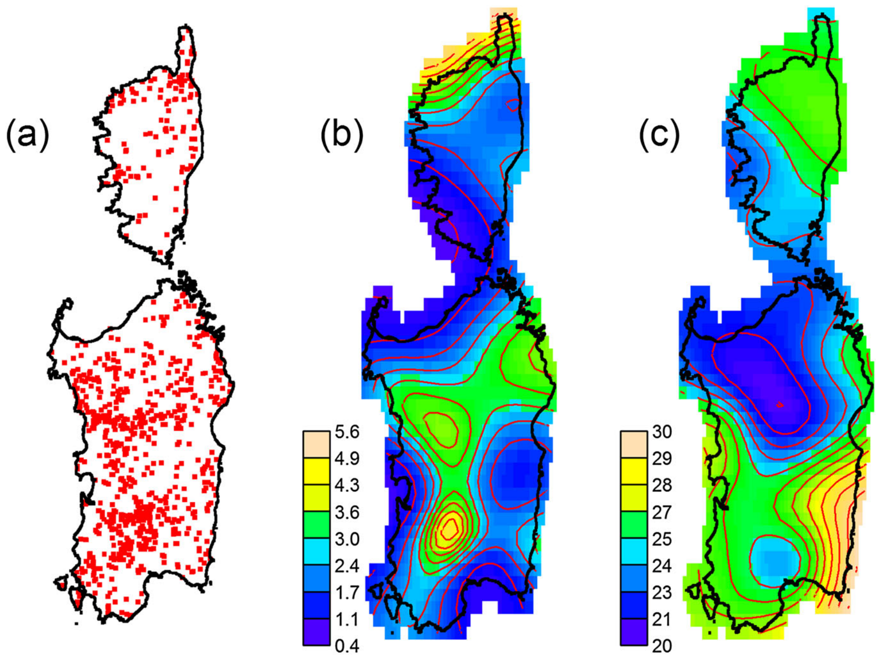

Figure 3. (a) Observed locations of large fires (>50 ha) for 1995–2009 and (b) conditional probability (percent) of large fire, per square kilometer per day, given ignition for Sardinia and Corsica. Conditional probabilities were estimated using spatial regression as described in the text. (c) Smoothed Fire Weather Index over all days with an ignition between 1995 and 2009

indicating larger fires on average. The most evident month by land cover exceptions were as follows: (1) transitional woodland shrub, which had a peak burning in August; (2) agroforestry areas, which had a maximum percentage of area burned in June; and (3) natural grasslands that showed relatively low burning rates for June and high rates for August. Plotting the total annual ignitions against the annual area burned (Figure 5(B)) showed the magnitude of wildfire activity in the study area among the land types. Nonirrigated arable lands and sclerophyllous vegetation accounted for the bulk of wildfire activity. The discontinuous urban fabric and complex cultivation land types, which had the highest ignition densities, were surpassed by the nonirrigated arable land and sclerophyllous vegetation in terms of total ignitions and area burned. Although fires in June accounted for much of the activity as measured by percentage of area burned and ignition density, their contribution to the total ignitions was reduced on an absolute basis, the one exception being the nonirrigated arable land. Overall, the differences among the land types in fire regime were substantial and reflected fuels and human factors related to ignitions. While some land types contributed more to the overall area burned (nonirrigated arable land), others had inherently high ignition densities (discontinuous urban fabric). It is likely that the relatively small fires on the latter land types are the result of better suppression activities and fragmentation of fuels (nonburnable fuels including roads, parking lots, and structures) in the urban areas.

4. STATISTICAL MODEL AND ESTIMATION

4.1. The model

For statistical analyses, we stratified the CLC types into three “regions”: (1) all forest and shrublands (FSr); (2) agricultural lands south of latitude 39°47′38″ (SAg); and (3) agricultural lands north of latitude 39°47′38″ (NAg) (Figure 5(B)). The stratification was developed after

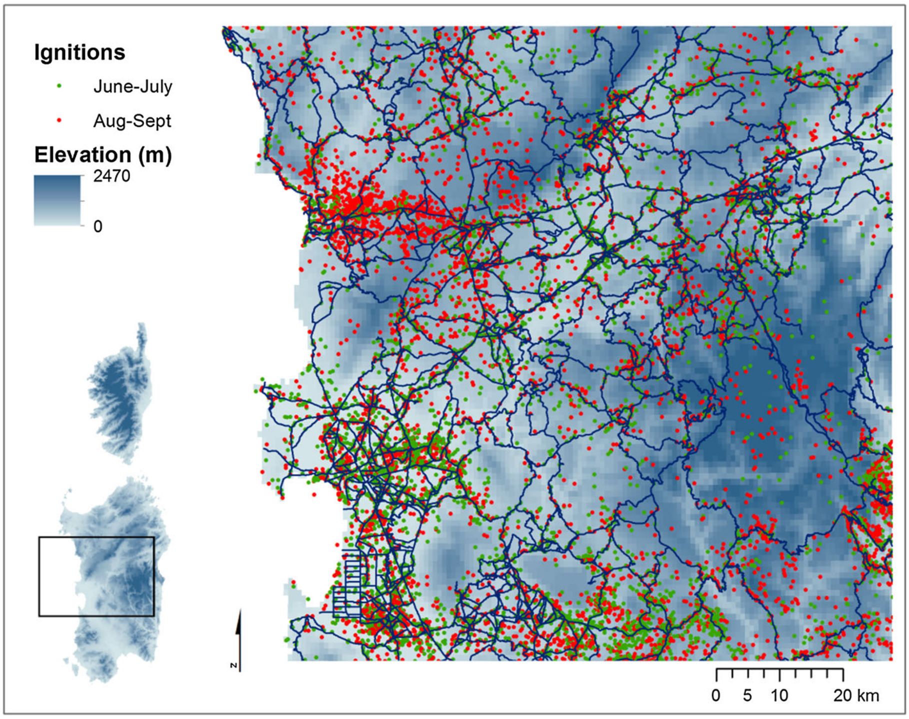

Figure 4. Fine-scale patterns of ignitions (1995–2009) showing roads and seasonal variation for a portion of west-central Sardinia

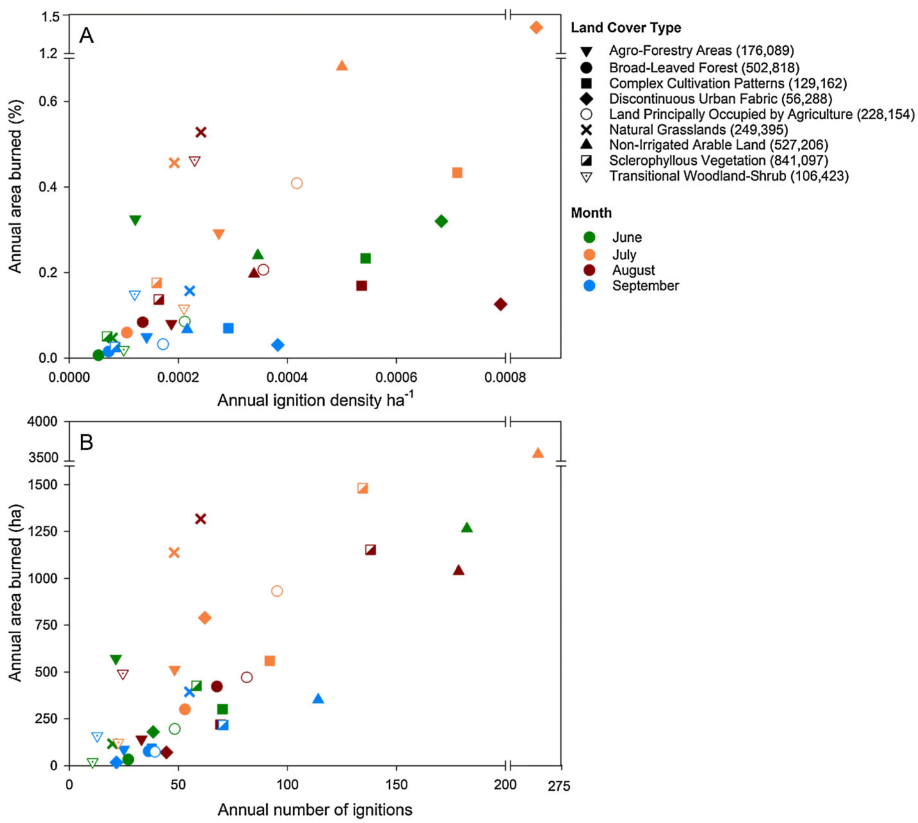

Figure 5. (A) Scatterplot showing annual ignition density and percent annual area burned for different Corine land cover types in Sardinia and Corsica from 1992 to 2009. (B) Scatterplot showing annual ignitions and annual area burned for different Corine land types in Sardinia and Corsica. In both panels, only land types with more than 330 ha burned per year are shown for clarity. Legend includes total hectares in each land-type category. Note break in *x* and *y* axes

the earlier exploratory analysis and information from previous studies, including Bajocco *et al.* (2010) who identified the SAg region as having a distinct fire season related to vegetation phenology and that overall ignition and large-fire occurrence in the forest and shrublands differed from the other land types. Thus, the stratification simplified the statistical modeling while preserving important differences among the Corine land types in terms of ignition and fire regime.

We used the framework of a spatial–temporal marked point process to model the fire occurrence data. Here, the location and timing of ignitions were the spatiotemporal point process, and the sizes of fires greater than size C were the marks. The lower cutoff point, C, of fire size was used because our interest was only in "significant" fires larger than a given size. Consider $\{x_i, y_i, \tau_i, u_i\}$, a realization of the random process, with (x_i, y_i) the location of i^{th} fire of size $u_i > C$, detected at time τ_i. We assume that the logarithm of fire sizes, $\log(u)$, is realizations of a generalized (truncated) Pareto distribution with shape and scale parameters, α and σ, respectively. Schoenberg *et al.* (2003) found that the truncated Pareto distribution gave the best fit for fires in southern California greater than 400 ha when compared with other commonly used distributions including the lognormal and the exponential distributions. We assess the goodness of fit of this model assumption later in the paper. The likelihood function for a discretized approximation of the process was set down as

$$\prod_{i=1}^{I}\delta_i(\boldsymbol{\theta}_1)^{N_i}\times[1-\delta_i(\boldsymbol{\theta}_1)]^{1-N_i}\times\frac{1}{\sigma_i(\boldsymbol{\theta}_3)}\times\left[1+\frac{\alpha_i(\boldsymbol{\theta}_2)(u_i-C)}{\sigma_i(\boldsymbol{\theta}_3)}\right]^{\left(-1-\frac{1}{\alpha_i(\boldsymbol{\theta}_2)}\right)\times N_i} \tag{1}$$

where N_i is equal to 1 if a fire of size $>C$ occurred, in kilometer× kilometer× day voxel i, and equal to 0 otherwise; $\delta_i(\boldsymbol{\theta}_1) = \Pr[N_i = 1|\boldsymbol{\theta}_1]$; and $\{\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \boldsymbol{\theta}_3\}$ are parameters describing the relationships of the anthropogenic and weather variables on the distributions of fire occurrence and size. For estimation purposes, the term $\delta_i(\boldsymbol{\theta}_1)$ is further split into two parts with

$$\delta_i(\boldsymbol{\theta}_1) = \Pr[R_i = 1|\boldsymbol{\theta}_{11}] \times \Pr[N_i = 1|R_i = 1, \boldsymbol{\theta}_{12}]$$

where R_i is equal to 1 if an ignition occurs in voxel i.

4.2. Estimation

The logarithm of the likelihood in equation (1) consists of three parts, each with a separate set of parameters. Consequently, estimation was performed in three stages. First, we estimated the probability of ignition (fire occurrence) as a function of the anthropogenic and weather variables. Next, we estimated the conditional probability of occurrence of a fire of size $>C$ given an ignition has already occurred at that location and time. Finally, we estimated the parameters for the distribution of fire sizes for fires $>C$. In the next sections, we set down the specific models we used to estimate the distributions and study the shape and significance of the relationships between explanatory variables and fire occurrence and size.

4.2.1. Probability of ignition

Let $p_{1ij} = \Pr[R_i = 1]$ be the probability of an ignition at location i and Julian day j, with R_i as defined earlier. We used the following logistic regression to characterize p_{1ij} as a function of explanatory variables identified in the exploratory analysis as potentially important:

$$Y_{1ij} = \text{logit}(p_{1ij}) = \alpha + \log(1/\pi) + s_1(drd_i, cor_i) + s_2(fwi_{ij}) + s_3(day_j, cor_i) \tag{2}$$

where *drd* is the distance from the ignition location to the nearest road, *cor* is a categorical variable specifying the land cover type (FSr, NAg, or SAg) at the ignition location, *fwi* is the fire weather index at the particular location and time of the ignition, and *day* is the day in year of the ignition. The term $\log(1/\pi)$ is an offset added to the intercept α, with π equal to the sampling proportion of voxels with no ignition (Brillinger, 2003). Sampling of the voxels with no ignition was carried out to create a manageable data size. The total number of voxels in the study area and the 15-year study period was over 187 million. The functions $s(\cdot)$ are nonparametric smooth functions of the covariates to be estimated from the data (Preisler *et al.*, 2004, 2009). Plots of the estimated smooth functions demonstrated the relationship between the explanatory variable and the log-odds of ignition. Other variables, including elevation, slope, aspect, distance to Corine urban areas, and number of inhabitants, were also examined as potential covariates before arriving at equation (2) as the model with the most significant and interpretable combination of variables.

4.2.2. Conditional probability of a large fire

Let $p_{2ij} = \Pr[N_i = 1|R_i = 1]$ be the probability that an ignition at location i and Julian day j will burn an area larger than C ha, with N_i and R_i as defined earlier. The following logistic regression was used to characterize p_{2ij} as a function of explanatory variables identified in the exploratory analysis as potentially important,

$$Y_{2ij} = \text{logit}(p_{2ij}) = \alpha(cor)_i + s_1(drd_i, cor_i) + s_2(fwi_{ij}) + s_3(day_j, cor_i) \tag{3}$$

where *drd*, *cor*, *fwi*, *day*, and $s(\cdot)$ are as defined earlier and $\alpha(cor_i)$ is an intercept that depends on the land cover type. Other variables, including elevation, slope, aspect, distance to urban areas, and number of inhabitants, were also examined as potential covariates before arriving at equation (3) as the model with the most significant and interpretable combination of variables.

We developed a reliability diagram (observed vs. predicted) using cross-validation, where predicted values for a given year were obtained using data from all other years. Observed fraction of large fires in the reliability diagram was developed by grouping large fires into classes according to the estimated linear predictor in equation (3). The diagram was used to assess model fit and to create a metric for predicting large-fire risk at a given ignition.

4.2.3. *Distribution of large fire size*

Assuming a generalized log-Pareto (log-gpd) function for the distribution of large fire sizes (fires $> C$), we estimated the scale and the shape of the distribution as a function of FWI. Initial analyses indicated that FWI was the only variable that had a significant effect on the distribution of large fire sizes among those included in the study. We produced quantiles for 500 simulations from the estimated log-gdp as a goodness-of-fit study of the gpd assumption. The simulated quantiles compared well with the observed quantiles of large fire sizes (Figure 6).

We checked the utility of the overall model for predicting a large fire given an ignition by simulating realization of a large fire (drawing from the binomial distribution with probability of response $\hat{p}_{2ij}$) at all ignition points and then simulating a large fire size (drawing from the log-gpd with the estimated parameters) at a simulated large-fire location. Next, we summed the simulated large fire sizes for each year and compared them with the observed total area burned by large fires. We defined a large fire as >50 ha because fires of this size almost certainly cause property damage in the study area and historically are responsible for most of the area burned. All statistical analyses were performed in R (R Development Core Team, 2011).

5. RESULTS

The relationship between distance to road and the log-odds of an ignition and large fire given ignition varied among the three different regions (Figure 7). The results showed that, for the NAg region, the log-odds of an ignition dropped dramatically with distance to road, but the log-odds of a large fire increased with increasing distance. A different relationship was observed for the SAg region, where ignition odds decreased with increasing distance to road, but the odds of a large fire decreased once the distance from road was beyond 2000 m. By contrast to the NAg and SAg regions, the relationship between distance to road and the log-odds of ignition for the FSr was weak. Thus, the probability of an ignition, and a large fire given an ignition, varied substantially among the regions, implying different fire ignition regimes and anthropic influence.

We next examined the effect of FWI on ignition probability and large fire (>50 ha) as a function of day within year for the three regions. The exploratory analyses presented in the previous section indicated that at broad space–time scales, there was a considerable lack of correspondence between the FWI and large-fire occurrence, when examined for the overall data set (Figure 3). To examine whether FWI is of potential value as an indicator of fire danger in both Sardinia and Corsica, it is important to understand the predictive value of FWI throughout the fire season after controlling for other covariates (in particular land type and distance to road). The model results showed that the relationship between FWI and ignition probability varied by day in year for the NAg and SAg regions, but not for the FSr (Figure 8). Specifically, in the SAg region, FWI was substantially less indicative of a high ignition probability early in the year compared with later (day of year 180 vs. 220). These results were amplified for the probability of a large fire, where a specific value of FWI early in the year translated to a much lower probability of a large fire later in the year. Again, the temporal change was most evident for the SAg region and weakest for the FSr region. The finding suggests that the relationship between FWI and wildfire probability changes over the course of the fire season, most likely because FWI does not measure human drivers of ignition, such as the timing of field burning related to specific agricultural and agro-pastoral practices. Incorporating these land use ignition drivers into the FWI could substantially improve its predictive ability in terms of ignition probability within the fire season.

To examine the effects of FWI on the overall (unconditional) probability of a large-fire occurrence ($p_{1ij} \times p_{2ij}$) while controlling for distance to road, we held the latter constant at 500 m and estimated the probability of a large fire for three monthly midpoints by region (Figure 9, bottom panels). In this way, the interactions between region and time of year could be examined without confounding effects associated with distance to road. We chose 500 m because it corresponded to the modal value for distance to road. The resulting model showed that FWI had the strongest influence on large-fire probability in the spring within the SAg region and the weakest influence in the fall. In July, the relationship between FWI and large fires was the same for all three regions, with large-fire probability rapidly increasing

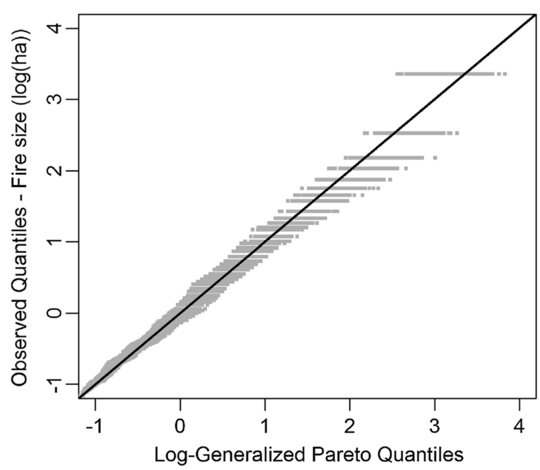

Figure 6. Quantiles of observed sizes (ha) of large fires (>50 ha) plotted against the quantiles of 500 simulations of the estimated generalized log-Pareto for Sardinia and Corsica

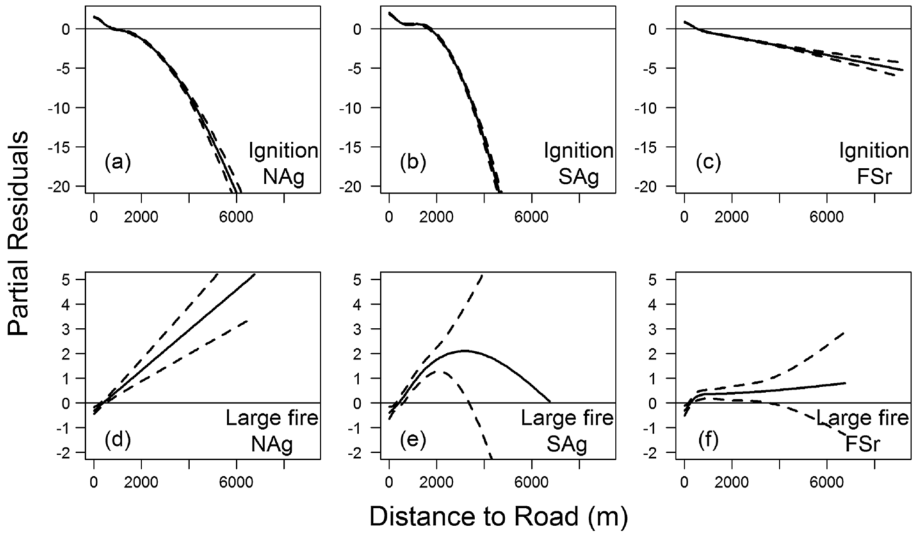

Figure 7. Estimated log-odds (partial residuals) versus distance to road for probability of ignition (top panels) and conditional probability of large fire (>50 ha) given ignition, for three land cover regions in Sardinia and Corsica. NAg = northern agricultural land defined by Corine level I "agricultural areas" north of latitude 39°47′38″; SAg = southern agricultural land defined by Corine level I "agricultural areas" south of latitude 39°47′38″; FSr = forest and shrublands as defined by Corine level I "forest and semi-natural areas" (EEA, 2002)

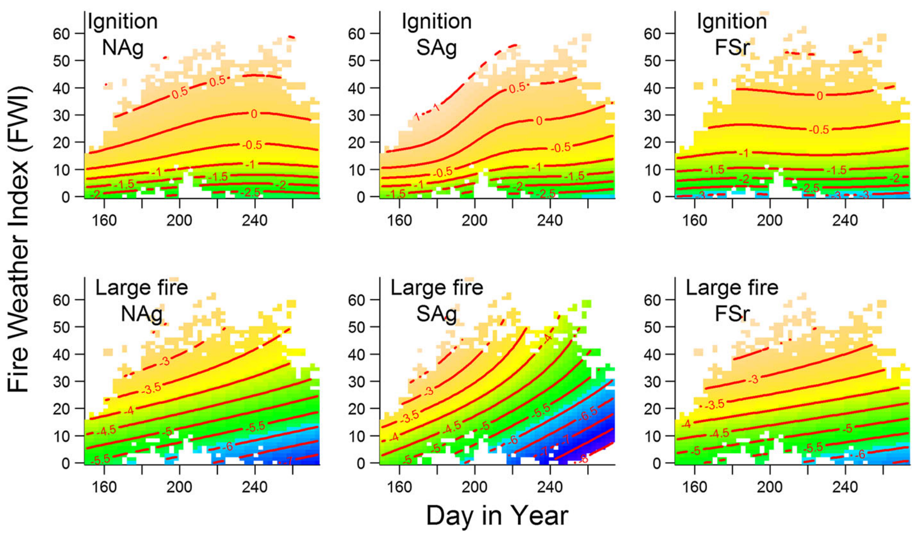

Figure 8. Estimated log-odds (partial residuals) for probability of ignition (top panels) and probability of large fire (>50 ha) given ignition (bottom panels) as a function of day in year and Fire Weather Index, for each of the three land cover regions in Sardinia and Corsica. Notice the higher-than-average log-odds earlier in the season on the southern agricultural land types. NAg = northern agricultural land defined by Corine level I "agricultural areas" north of latitude 39° 47′38″; SAg = southern agricultural land defined by Corine level I "Agricultural areas" south of latitude 39°47′38″; FSr = forest and shrublands as defined by Corine level I "forest and semi-natural areas" (EEA, 2002)

with increasing FWI. By contrast, the relative effect of FWI among the three regions in September was the opposite from that observed in spring. For instance, relatively large probabilities were observed for the FSr at a given FWI compared with the agricultural regions (SAg and NAg).

To understand distance-to-road effects independent of seasonal changes and FWI, we estimated large-fire probabilities while holding FWI and date constant (Figure 9, top panels). The FWI values were chosen to represent the upper 75th percentile FWI value for each of the months of June, July, and September. The selected dates were June 15, July 30, and September 15 and were chosen to sample the fire season at three distinct points. The results show that distance to road had the strongest effect on large-fire probability in the early part of the season (June 15) in the SAg region. A lesser effect was observed for the NAg region and only a slight effect for FSr. In June, roads had an interesting effect on large-fire probability in the SAg, where an increase was observed at a distance of about 1000 m. Late in the season (September 15), distance to road had a lesser effect in all three regions.

The reliability diagram (Figure 10) illustrated the overall ability of the model to predict the occurrence of a large fire given ignition. This type of figure may have value to managers as a predictive tool where the estimated linear predictor is an index for large-fire risk. For example,

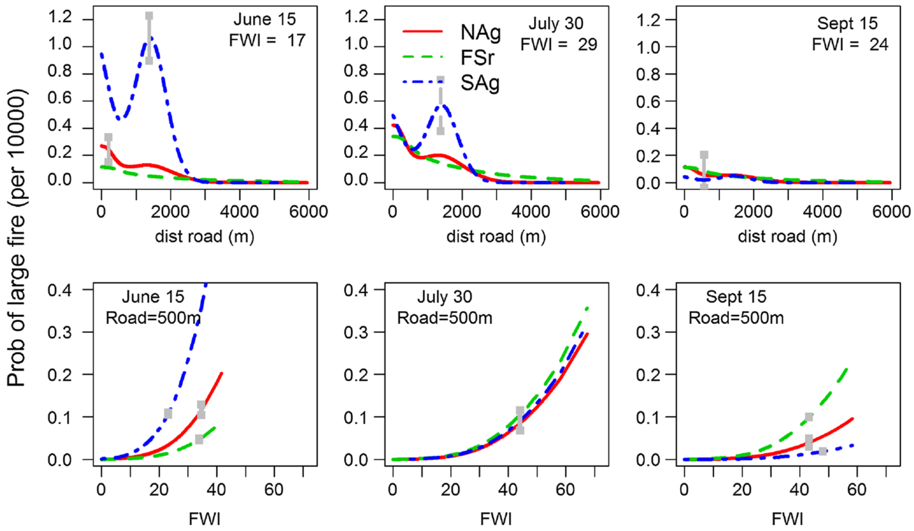

Figure 9. Estimated probability of a large fire (>50 ha) for three selected days in the year and for three land cover regions in Sardinia and Corsica as a function of (top panels) distance to road, evaluated at the stated Fire Weather Index (FWI) values (top panels), and as a function of FWI with distance to road held constant at 500 m (bottom panels). The gray vertical bands are the 95% confidence limits at selected points along the *x*-axis. The FWI values are the upper 75th percentile values for each of the months of June, July, and September. NAg = northern agricultural land defined by Corine level I "agricultural areas" north of latitude 39°47′38″; SAg = southern agricultural land defined by Corine level I "agricultural areas" south of latitude 39°47′38″; FSr = forest and shrublands as defined by Corine level I "forest and semi-natural areas" (EEA, 2002)

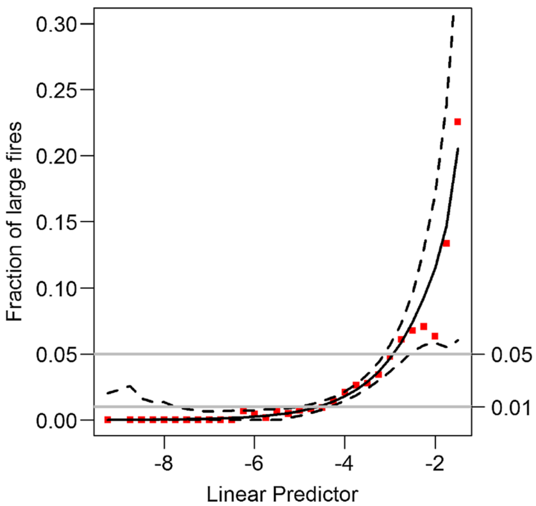

Figure 10. Observed fraction of large fires (red squares, >50 ha) plotted against estimated linear predictor (log-odds of an ignition becoming a large fire) superimposed with the cross-validation estimates of conditional probability of a large fire (smooth curve) and approximate pointwise 95% confidence bounds (dashed lines) for Sardinia and Corsica. This linear predictor may be used as a fire danger index that combines weather and anthropogenic factors

if the index (linear predictor) for a given ignition is −6, then our model indicates a less than 1% chance of the ignition burning more than 50 ha. Alternatively, an index of −2 indicates a 15% chance of the ignition burning more than 50 ha, albeit with a large standard error. The large standard error values observed for linear predictor values greater than 2 are most likely due to the small number of large fires in our study area.

The only explanatory variable that we found to have an effect on the distribution of large fire size was FWI. There was a marginally significant increase ($P < 0.1$) in the logarithm of large fire sizes with increasing FWI up to 20, with no further increase with greater FWI values. The distribution of total area burned by large fires per year (given ignition) developed from 500 simulations of the estimated distributions was compared with the observed total area burned by large fires (Figure 11). The model appeared to explain some of the among-year variation in the burned area. Because FWI was the only variable that changed among years, it is the main predictor variable in the model at the yearly time-scale. However, there clearly are other factors influencing the process, with substantial differences between observed and predicted in 1999, 2008, and 2009, for example. We examined additional explanatory variables derived from FWI values and found that the total annual area burned by just large fires (>50 ha) appeared to be closely related to the number of days where FWI exceeded 40 (Figure 11). This apparent correlation between FWI and area burned at the timescale of a fire season may be useful for future studies on potential climate impacts on wildfire area burned. Addition explanatory variables including fuel loading maps might further improve the relationship between FWI-derived explanatory variables and annual area burned.

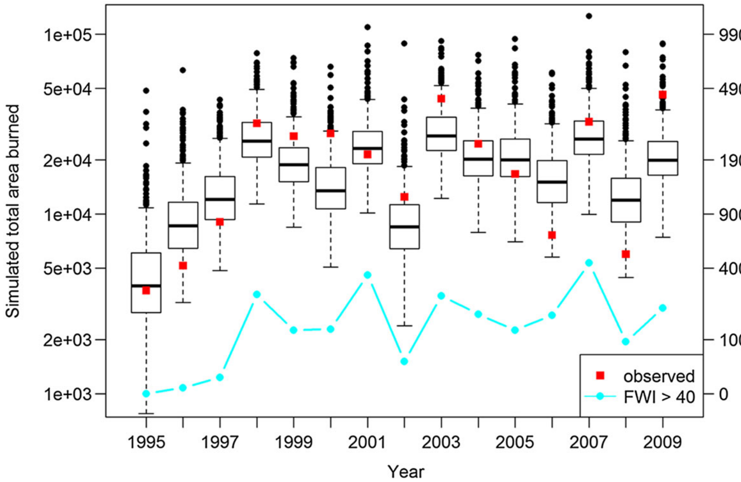

Figure 11. Box plots of 500 simulations of total area burned per year by large fires (>50 ha) given the observed ignitions in Sardinia and Corsica. Simulation values in the box plots are based on the estimated generalized log-Pareto (log-gpd) and conditional probability of large fires. The box plots represent the expected conditional distribution of total area burned (ha) given the ignitions. Red squares are the observed total area burned (ha) by large fires. The blue curve at the bottom (with values given by the right axes) indicates the observed number of ignition days per year with Fire Weather Index (FWI) > 40

6. DISCUSSION

This study identified spatiotemporal ignition patterns in Sardinia and Corsica at a scale that is useful for managers concerned with fire prevention and fire danger prediction programs. We showed the combined effects of several explanatory variables including distance to roads, day of year, and the FWI. These finer-scale patterns are relevant for wildfire risk mitigation and prevention planning programs and are useful for building risk and hazard indices (Verde and Zezere, 2010). Maps created from the statistical models for specific periods during the fire season can potentially be used to prioritize specific locations for fire prevention and fuel modification via mechanical treatments and prescribed fire activities. In some areas, these fuel breaks might constitute land use changes to eliminate agricultural practices that create fuel beds with fast spread rates and high flame length as part of a long-term solution to reduce ignition frequencies and burned area. The maps can also be used to target fire detection efforts along particular road segments at specific times of the year where ignition and large-fire probabilities are highest.

In terms of the magnitude of the observed effects, we estimated about an eightfold increase in the odds of a large fire on days/locations with FWI = 60 versus days/locations with FWI = 30 regardless of the time of year or cover type. For example, for a given location with an estimated risk (probability of a large fire) equal to 0.3 per thousand on days with FWI = 30, risk will increase to 2.4 per thousand if FWI increased to 60. Moreover, we estimated that the odds of a large fire in the SAg land type was approximately 10 times larger than the FSr land type near roads early in the fire season. Conversely, toward the end of the fire season (around September), we estimated the odds of a large fire in the SAg land type at about half that for FSr, indicating that there are substantial interactions between time of year and the land types in terms of large-fire occurrence.

In previous work on fires in Sardinia, De Angelis *et al.* (2012) showed a strong association between vegetation phenology based on remotely sensed data (Normalized Difference Vegetation Index) and the spatiotemporal wildfire distribution. That study and related work emphasized bioclimatic timing as the primary driver of fires, and the results suggested that fuel phenology (i.e., curing) rather than total fuels was the more important explanatory variable (Bajocco *et al*., 2010). Other studies in the Mediterranean region have suggested that climatic conditions related to fuel phenology are more important than conditions that contribute to high fire danger (Vázquez *et al*., 2002). Most of the previous studies have made use of the Corine land-type data to explain fire occurrence (Nunes *et al*., 2005; Catry *et al*., 2009; De Angelis *et al*., 2012; Oliveira *et al*., 2012). In our study, we examined more closely the interactions among CLC type, time of year, distance to road, and FWI and their combined effects on ignition probability and large-fire occurrence. Rather than predicting fire occurrence at the scale of the Corine land-type polygons, we used continuous explanatory variables and generated probability surfaces (at a 1-km^2 scale) describing both ignition and large-fire likelihoods. We also incorporated daily, fine-scale weather effects into the models via the FWI, which are not always captured with broader climatic indices of fuel phenology. Weather variables used in the FWI account for daily occurrence of rain, temperature, relative humidity, and wind, which can be important predictors of wildfire under a range of fuel phenologies, especially in the case of forests with high dead-surface fuel loadings. We also included a human component in the analysis as represented by distance from roads, as road effects on ignition probabilities are well established in previous research in other Mediterranean regions. Roads and other anthropogenic features are of strong interest for wildfire mitigation because more than 90% of fires are ignited by humans in the region.

A common finding in studies of fire occurrence is that spatiotemporal patterns of ignitions are substantially different than those for large fires. Many factors determine whether fires escape initial attack and become large fires, including suppression resources, response time, weather conditions, fuel contagion, and rate of spread to name a few (Preisler *et al*., 2004; Moreira *et al*., 2010). In the current study, we observed substantial differences between the probability of an ignition and the probability of an ignition becoming a large fire. Specifically, large-fire probability increased with distance to road, while ignition probability decreased. However, there were interactions with both day within year and land cover region. For instance, large-fire probability was not related to distance from road in the FSr region but was positively associated with roads in the NAg region. Moreira *et al*. (2010) also found that large fires were inversely related to population density and were most prevalent in shrublands and forests away from roads, although a larger threshold was used for his study of large fires in Portugal (500 vs. 50 ha). Likewise, our results showed that ignition probability decreased with distance to road in the agricultural regions, similar to results found elsewhere with road density (Vasconcelos *et al*., 2001; Catry *et al*., 2009), but we did not observe this same effect in the FSr region. We also observed clear differences in the probability of a large fire in the NAg versus SAg regions. The southern area is drier, with a fire season that can start at least 2 weeks earlier than in the north, and the area contains intensive and specialized agricultural crops intermixed with a larger human presence compared with the northern region.

Another interesting result is the relationship seen between the total number of days within the fire season where the FWI exceeded 40 and the total area burned by large fires (> 50 ha). This general relationship appeared to explain much of the annual variation in area burned over the period studied. These types of relationships can be used to examine, for instance, the potential impacts of climate change on wildfire activity.

The effects of fire suppression likely contributed to the observed fire occurrence patterns, but data to statistically examine these effects do not exist. Fire suppression activities are greatly facilitated by roads, and thus, our observation that the probability of a large fire increases with distance from road may be in part due to decreased suppression efficiency in these areas. Roads provide key access for initial attack resources and thus affect the probability that an ignition becomes a large fire but also are a convenient location for arsonists to ignite fires as well. Suppression resources are also mobilized in periods of high FWI throughout the study area, and their increased availability during these periods might have actually decreased large-fire occurrence at high FWI. Without spatiotemporal data on the deployment of suppression resources during the fire season, it is difficult to assess the extent to which suppression accounts for the observed patterns in fire occurrence and large fires.

A wide range of approaches has been applied to the problem of wildfire hazard and risk assessment, ranging from empirical studies of ignition and large-fire patterns (Catry *et al*., 2009; Verde and Zezere, 2010) to simulation modeling where probabilities are estimated by simulating wildfires with Monte Carlo sampling of weather (Miller and Ager, 2012; Salis *et al*., 2013a, 2013b). In a study by Verde and Zezere (2010), ignition models were combined with indices of human ignition drivers to build composite risk models. Both empirical and simulation studies can contribute to the problem of risk assessment and mitigation, the different approaches having strengths and weaknesses depending on the fire regime at hand. For instance, while empirical studies can provide valuable insights into the human and ecological factors that contribute to ignition patterns and large fires, wildfire simulation models are needed to map fine-scale burn probabilities and test the effectiveness of specific mechanical fuel reduction treatments (Ager *et al*., 2010, 2011). Results from the current study can help refine simulation models used in the study area (Salis *et al*., 2013a, 2013b) by providing more detailed ignition probability maps that capture important space–time patterns in wildfire occurrence and burn probability. Spatial information from empirical and simulation modeling can also be combined to couple human and biophysical drivers of wildfire risk. For example, in the work of Salis *et al*. (2013a), an empirically derived ignition probability map was combined with simulation outputs describing the potential fire size as a function of ignition location to create an index of fire potential. Maps of these outputs can be used for mitigation activities, such as prioritizing the placement of fuel breaks along roads and fire prevention patrols during peak fire season.

This study also provides insights in the use of the FWI as an indicator of fire danger during the fire season. FWI could be adopted in Sardinia to position suppression resources and used in conjunction with other fire danger models such as the IFI (Sirca *et al*., 2006; Fiorucci *et al*., 2008). When the models indicate high values of fire danger, the Forest Service and the Civil Protection can alert specific areas, and they can increase fire prevention activities with patrols and suppression resources. The outputs show that the relationship between FWI and the probability of an ignition and large fire varies over time and space. While FWI had some effect on the probability of a large-fire occurrence, the total area burned by fires that reached 50 ha was not related to this variable. The weak relationships we observed for FWI could be in part due to the fact that many fires are ignited as part of agricultural practices for specific crops, and the timing of these fires has more to do with the crop production cycle rather than FWI. Field burning for agricultural production is tied to fuel phenology in Sardinia and Spain (Vázquez *et al*., 2002; Bajocco and Ricotta, 2008), and thus, high fire danger indices are most meaningful when the fuel phenology permits burning. It is also possible that the lack of a significant effect of FWI on the size of large fires was partly caused by the relatively small sample of weather stations (11) used to generate the smoothed map used to assign an FWI to each ignition point.

Overall, as stated by De Angelis *et al*. (2012), the wildfire distribution in Sardinia results from complex interactions between ignition sources, weather conditions, vegetation, and topography. Previous studies have incorporated human drivers as qualitative variables using Corine land type as surrogates (e.g., Bajocco and Ricotta, 2008) and measured the influence of fuels in terms of phenological status by land type. Given that the fire regime in terms of ignitions in the Mediterranean region is ultimately controlled by human behavior, variables related to human activities are very important, particularly in southern Europe, as the vast majority of wildfires have human origin (EEA, 2008). The current debate between weather and fuel amount and phenology controlling fire behavior could benefit from the recognition that the effects of different factors on fire occurrence can vary among ecosystems and across spatial and temporal scales (Catry *et al*., 2009). The complex interactions among FWI, anthropogenic variables, and land cover types could be added to existing fire danger systems to build improved spatiotemporal risk maps and uncertainty estimates. The latter effort could potentially benefit from the estimated linear predictor we developed in this study, which combined FWI, anthropogenic effects, and season as an index for large-fire risk. Future analyses that incorporate specific agricultural practices and arson behavior will further improve these mapping efforts, collectively leading to improved wildfire predictive capabilities in the Mediterranean region and better decision support tools for fire protection agencies.

ACKNOWLEDGEMENTS

We thank Michelle Day for assistance with various aspects of the paper. The authors would also like to thank the Forest Service of Sardinia and Corsica for their collaboration in this study. This work was funded by several sources including the GEMINA Project—MIUR/MATTM no. 232/2011, the Extreme Project (Sardinia Regional Project, CRP-25405, LR. 7/2007), and the “Modeling approach to evaluate fire risk and mitigation planning actions” (POR SARDEGNA FSE 2007–2013, Asse IV Capitale umano, Linea di Attivita` l.3.1).

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