

Evidence of selective burning in Sardinia (Italy): which land-cover classes do wildfires prefer?

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Abstract The objective of this paper is to identify land-cover types where fire incidence is higher (preferred) or lower (avoided) than expected from a random null model. Fire selectivity may be characterized by the number of fires expected in a given land-cover class and by the mean surface area each fire will burn. These two components of fire pattern are usually independent of each other. For instance, fire number is usually connected with socioeconomic causes whereas fire size is largely controlled by fuel continuity. Therefore, on the basis of available fire history data for Sardinia (Italy) for the period 2000–2004 we analyzed fire selectivity of given land-cover classes keeping both variables separate from each other. The results obtained from analysis of 13,377 fires show that for most land-cover classes fire behaves selectively, with marked preference (or avoidance) in terms of both fire number and fire size. Fire number is higher than expected by chance alone in urban and agricultural areas. In contrast, in forests, grasslands, and shrublands, fire number is lower than expected. In grasslands and shrublands mean fire size is significantly larger than expected from a random null model whereas in urban areas, permanent crops, and heterogeneous agricultural areas there is significant resistance to fire spread. Finally, as concerns

mean fire size, in our study area forests and arable land burn in proportion to their availability without any significant tendency toward fire preference or avoidance. The results obtained in this study contribute to fire risk assessment on the landscape scale, indicating that risk of wildfire is closely related to land cover.

Keywords Fire number · Fire selectivity · Fuel fragmentation · Landscape analysis · Mean fire size · Permutation methods

Introduction

Disturbances spreading through the landscape, for example wildfires, are essential processes in modeling landscape structure and functioning. In fact, disturbance regimes and landscape patterns have strong mutual interactions. Disturbances spread across the landscape as a function of the abundance and arrangement of disturbance-susceptible habitats (Turner et al. 1989). In turn, landscape patterns are conspicuously determined by disturbance frequency, intensity, and extent (Pickett and White 1985; Krümel et al. 1987). These mutual interactions between disturbance regimes and landscape structure may become complex, resulting in dynamic patterns through time (Roberts 1996; Lloret et al. 2002).

Like other disturbances, fire may spread from a local epicenter to cover large areas, with propagation

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rate enhanced or retarded by the spatial arrangement of fuel across the landscape. Thus, the amount of fuel and its spatial distribution are basic factors in explaining fire ignition and propagation, because the discontinuity of fuel load will produce changes in fire-propagation rates (Burgan et al. 1998; Lloret et al. 2002).

In turn, there is a close relationship between the type of land cover and the fuel characteristics (Turner and Romme 1994). If the several land cover categories of a given landscape were equally fire-prone, then fires would occur randomly; actually certain land-cover types are more susceptible to fire than others (Forman 1997). Therefore, we expect that the spatial pattern of fire occurrence will be affected to some extent by the arrangement of the different land-cover types, for which the probability of fire ignition and fire spread will both be different (Morvan et al. 1995; Moreira et al. 2001; Nunes et al. 2005).

In this view, understanding the spatial pattern of fire locations is a key issue for predicting fire occurrence and for understanding the role of fire in landscape processes. This requires a good preliminary understanding of the causes of burning, and of the natural and cultural landscape features that affect the location of fires (Stolle et al. 2003). The objective of this study is thus to quantify patterns of fire occurrence at the landscape level in Sardinia (Italy) during the period 2000–2004 to determine the extent to which fires are selective regarding land cover. That is, to identify land-cover types where fire incidence is higher (preferred) or lower (avoided) than expected from a random null model.

To analyze fire selectivity we used methods originally designed to study resource selection by animals (Manly et al. 1993; Alldredge et al. 1998). In accordance with Moreira et al. (2001) and Bond and Keeley (2005) we considered fire as an “herbivore” with variable preferences for different resources (i.e., land-cover types). If several land-cover types were equally fire-prone, in terms of both combustibility and chances of ignition, fires would occur randomly in the landscape with an equal proportion of available and burnt land-cover types. Actually certain land-cover types are more fire-prone than others. That is, they represent a selective resource for fires. In this sense, fire is considered selective when resources are used disproportionately to their availability (Moreira et al. 2001; Nunes et al. 2005).

Study area

The island of Sardinia is located between 38° 51' N and 41° 15' N latitude and between 8° 8' E and 9° 50' E longitude, and covers roughly 24,000 km². Sardinia is characterized by a complex physical geography, with prevalently hilly topography and extreme heterogeneity in geological and morphological features. The highest elevation is 1,834 m; average elevation is 338 m.

The climate of Sardinia is typically Mediterranean with hot and dry summers and mild and rainy winters. Average annual rainfall ranges from less than 500 mm in the coastal areas to more than 900 mm in the inner mountainous regions. Mean annual temperature ranges from 11 to 17°C.

According to Bocchieri (1995) the island's flora comprises approximately 2,054 species, 10% of which are endemic. Land use along the coast and the main river valleys is dominated by agriculture that covers about 45% of the study area. In the interior areas, forest stands combined with pastures and shrublands prevail. The principal formations include *Quercus ilex* and *Quercus suber* forests. At higher elevations the sclerophyllous oak forests merge with broadleaved forests of *Quercus pubescens* and *Castanea sativa*.

Materials and methods

Data

Based on 13,377 records of the Regional Forest Service on individual fires from 2000 to 2004, we compiled a five-year fire history of Sardinia. For each fire, the data collection includes a field estimate (measured in hectares) of the burnt area and the geographic coordinates of its ignition point. The database contains all fires that were recorded by the Forest Service, and is assumed to be complete and reliable down to the smallest fires. The recorded size of burnt area ranges between 0.01 and 1,815 ha. The total surface burnt during 2000–2004 is approximately 88,800 ha.

Fire size distribution in the 2000–2004 period examined is adequately described by a power-law over many orders of magnitude (Malamud et al. 1998; Ricotta et al. 1999) with 8,782 fires that are

less than 1 ha in size and only 172 fires that are larger than 100 ha. While these large fires represent less than two percent of the fires recorded, they account for fifty-three percent of the total area burnt in Sardinia from 2000 to 2004 (Fig. 1).

Like in most Mediterranean regions, the large majority of fires included in this analysis are human-caused rather than “natural” in origin (unfortunately, detailed statistics of the causes of fire ignition are not available for the study area). Nonetheless Figs. 2 and 3 clearly show fire in Sardinia to be a process largely governed by climate with a peak of the fire season occurring during the hottest and driest part of the year. Figures 2 and 3 are, respectively, mean monthly number of total fires and hectares burnt for the period 2000–2004. As shown in both figures, fire is strongly seasonal; 68% of fires and 74% of area burnt occur between July and September with a peak of fires and hectares burnt during July.

Land-cover classification

As noted by Nunes et al. (2005), in principle, fire selectivity is best analyzed using fuel maps containing quantitative characterizations of fuel types based on stand structure and composition, surface and ladder fuels, and forest floor cover (Anderson 1982; Nadeau and Englefield 2006).

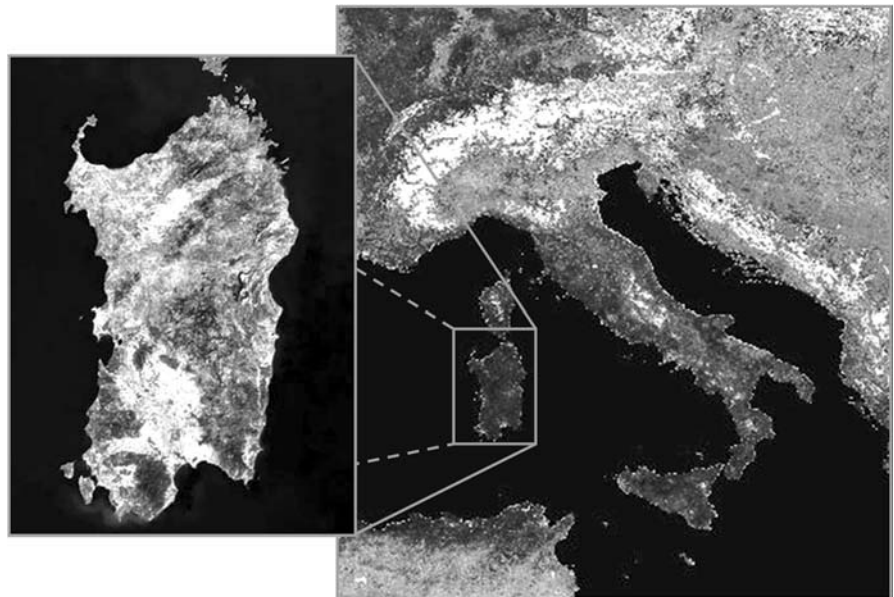
However, because of the complex nature of fuel characteristics, a fuel map is considered one of the most difficult thematic layers to build up, especially for large areas and on coarse spatial scales (Keane et al. 2001; Lasaponara and Lanorte 2007).

Castro and Chuvieco (1998) adopted an integrated multisensor approach based on Spot and Landsat images to perform a fuel-type classification of Chile based on a modified version of Anderson’s (1982) fuel models. Nonetheless, the correspondence between remotely sensed land-cover classes and fuel types remains an open question. Therefore, we used a seven-class land-cover map derived from CORINE land-cover data updated for the reference year 2000 (CLC2000). The CLC2000 classes were aggregated into seven macro-classes (Table 1). Because of the relative homogeneity of the amount and spatial continuity of fuel load within each class, the seven macro-classes were considered adequate to study fire-incidence patterns on the landscape scale. Bare soils, wetlands, and water bodies, regarded as non-combustible, were excluded from further analysis.

Statistical analysis

To obtain information about the number of fires and the burnt surface within each land-cover class during 2000–2004, the coordinates of the ignition points of

Fig. 1 Location of the study area



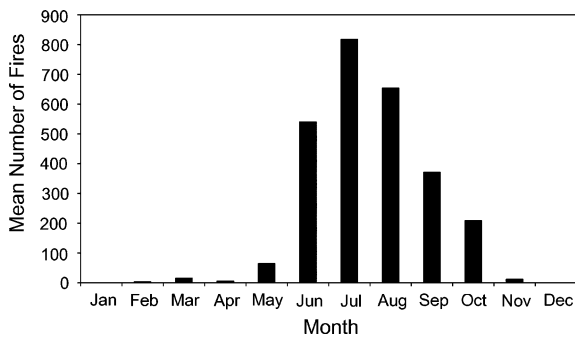


Fig. 2 Mean monthly number of fires in Sardinia for 2000–2004

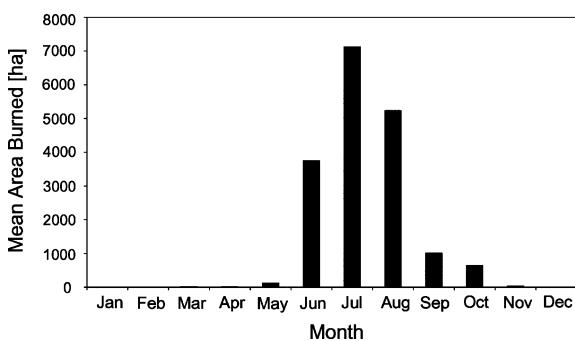


Fig. 3 Mean monthly hectares burnt in Sardinia for 2000–2004

all fires were overlaid on the land-cover map of Sardinia. The whole size of each wildfire was then associated with the land-cover class that contained its ignition point. Although this procedure may overestimate or underestimate the burnt surface within

Table 1 Land-cover types used to analyze fire selectivity in Sardinia

CORINE land-cover types	Areal extent (ha)
Urban areas	66,766.95
Arable land	527,423.90
Permanent crops	49,625.25
Heterogeneous agricultural areas	469,443.95
Forests	387,960.40
Natural grasslands and pastures	162,440.94
Transitional woodland-shrub and sclerophyllous vegetation	682,507.76
Total	2,346,169.15

For each land-cover type the extent in the study area is shown

specific land-cover classes, it has the advantage over other proposed methods (see, e.g., Moreira et al. 2001; Nunes et al. 2005) that it does not require accurate mapping of each burnt area for analyzing fire selectivity. This enables fire selectivity to be analyzed on the basis of the complete fire history of a given region instead of using just a limited subset of mapped fires.

Fire patterns may be characterized by the number of expected fires in a given area and by the mean surface that each fire will burn. These two components of fire pattern are usually affected by different processes. For instance, in our study area more than 90% of fires are human-caused. Therefore, the number of fires is generally related to population density, agricultural practices, grazing pressure, etc. (Moreira et al. 2001). By contrast, fire size is more dependent on spatial variation of fuel (Cumming 2001), which is, in turn, related to landscape structure (e.g., mainly physical and vegetation features). We therefore analyzed fire selectivity in terms of number of events and burnt surface separately by means of two independent statistical tests.

To determine whether the number of fires in the examined cover classes is significantly different from random, we constructed the following Monte Carlo simulation. The 13,377 fires that occurred in Sardinia during 2000–2004 were randomly reassigned to the land-cover classes such that the probability of assignment of each fire to a given land-cover class was kept equal to the relative extent of that class. The null hypothesis is that fires occur randomly across the landscape such that there is no difference between the relative abundance of fires in each land-cover class and the relative extent of each class within the analyzed landscape.

Next, we compared the actual number of fires in each land-cover class with the results from 1,000 random simulations, each based on 13,377 fires. For each land-cover class, *P*-values (two-tailed test) were computed as the proportion of Monte Carlo-derived values that were as low or lower (as high or higher) than the actual values.

At the same time we tested whether the burnt surface in each land-cover class is significantly different from random. First, we computed the mean fire size in each land-cover class. Next, we compared the observed values with a Monte-Carlo simulation for which, by keeping the number of fires in each

land-cover class constant, we randomly reassigned the burnt surfaces of each fire. In this way we created landscapes in which the surface burnt by each fire is distributed at random with respect to land cover. The P -values (two-tailed test) were obtained as the proportion of 1,000 permutations for which the mean random fire size of each land-cover class is as low or lower (as high or higher) than the actual value.

Results

The results of our analysis of fire selectivity in Sardinia are shown in Tables 2 and 3. According to

our Monte–Carlo simulations, fire incidence in terms of number of fires is selective for all land-cover classes with very high significance ($P < 0.001$; Table 2). The number of fires is higher than expected from a random null model in urban areas and in all agricultural classes. By contrast, the number of fires is lower than expected in forests, grasslands, and shrublands.

Mean fire size is significantly larger than expected in grasslands and shrublands, with very low P -values (Table 3). On the other hand, urban areas, permanent crops, and heterogeneous agricultural areas are less likely to be burnt whereas arable land and forests do not show any significant result as concerns mean fire size at the $P = 0.05$ level.

Table 2 Results from selectivity analysis of fire number

CORINE land-cover types	Number of fires	P -values	Lower limit	Upper limit
Urban areas	1033	$P < 0.001$	306	435
Arable land	4207	$P < 0.001$	2870	3160
Permanent crops	651	$P < 0.001$	232	347
Heterogeneous agricultural areas	3931	$P < 0.001$	2526	2824
Forests	862	$P < 0.001$	2087	2352
Natural grasslands and pastures	746	$P < 0.001$	837	1002
Transitional woodland-shrub and sclerophyllous vegetation	1947	$P < 0.001$	3728	4066

For each land-cover type the actual number of fires during 2000–2004 is shown with the P -values (two-tailed test) obtained from 1,000 Monte Carlo simulations. In the last two columns, the upper and lower limits of the Monte Carlo simulations are also shown. In the second column, bold characters are associated with land-cover types that are more likely to be burnt whereas normal characters are associated with land-cover types that are less likely to be burnt

Table 3 Results from selectivity analysis of mean fire size

CORINE land-cover types	Mean fire size (ha)	Fire rotation period (year)	P -values	Lower limit	Upper limit
Urban areas	1.21	267.08	$P < 0.001$	3.44	11.37
Arable land	7.54*	83.14	$P = 0.092$	4.40	8.56
Permanent crops	1.61	236.74	$P < 0.001$	2.77	14.08
Heterogeneous agricultural areas	5.05	118.24	$P = 0.002$	4.89	8.51
Forests	7.03*	320.11	$P = 0.346$	3.35	11.64
Natural grasslands and pastures	14.68	74.17	$P < 0.001$	3.29	14.63
Transitional woodland-shrub and sclerophyllous vegetation	9.20	190.51	$P = 0.008$	4.41	9.84

For each land-cover type the actual mean fire size during 2000–2004 is shown together with the P -values (two-tailed test) and the upper and lower limits obtained from 1,000 Monte Carlo simulations. The third column shows the fire rotation period, i.e. the number of years necessary to burn an area equivalent to the total surface of the corresponding land-cover class. In the second column, bold characters are associated with land-cover types that are more likely to be burnt whereas normal characters are associated with land-cover types that are less likely to be burnt

*Not significant at the $P = 0.05$ level

Discussion

A detailed knowledge of how fire “uses” the landscape (i.e., which land-cover types are preferred or avoided by fire) is important for understanding the role of fire in landscape processes, with obvious consequences for land management and fire-prevention issues (Botelho et al. 1998).

Because some land-cover classes are more “fire-prone” than others, these classes can be defined as selective resources for fire. This broad concept of landscape selectivity for fires can be further refined to analyze the interaction between the chances of ignition of selected landscapes, their fuel load and fuel continuity, and how quickly the fires are controlled.

In this view, previous authors (Moreira et al. 2001; Nunes et al. 2005) studied the land-cover selectivity of wildfires focusing solely on fire size. By contrast, based on complete fire-history data in Sardinia for the period 2000–2004, we analyzed fire preferential behavior in terms of both number of events and mean fire size. This is because these two variables are generally independent of each other; fire number is usually connected with social, economic and cultural drivers whereas fire size is mainly controlled by fuel load and fuel continuity.

As shown in Tables 2 and 3, fire can select negatively a certain land-use class in terms of expected number of fires; at the same time, the same class can be selected positively as concerns mean fire size, or vice versa.

In forests, shrublands, and grasslands where human pressure is not very intense, the number of fires is lower than expected from a random null model (Table 2). On the other hand, natural and seminatural classes are generally characterized by large homogeneous patches of relatively high fuel load that favor rapid fire spread through the landscape. Accordingly, in grasslands and shrublands mean fire size is significantly larger than expected from a random null model whereas forests tend to burn in proportion to their availability (Table 3).

Also, looking at these natural and seminatural classes, there is a clear inverse relationship between mean fire size and the fire rotation period sensu Vazquez et al. (2002); i.e. the number of years necessary to burn an area equivalent to the total surface of the corresponding land-cover class. For

instance, during 2000–2004, in grasslands mean fire size is larger than in forests, because grasslands have finer fuels that dry more quickly and can therefore burn easily after short periods of dry weather. In contrast, forest fuels are usually coarser, and take longer to dry; therefore, they can burn only after longer (and hence less frequent) periods of dry weather. Because of their intermediate fuel size, shrublands show intermediate behavior between forests and grasslands in terms of both mean fire size and fire rotation period.

On the other hand, for all urban and agricultural lands fire shows a significant preference in terms of fire number and a marked avoidance as concerns mean fire size; for urban areas, arable land, permanent crops, and heterogeneous agricultural areas the number of fires is significantly higher than expected by chance alone (Table 2). This is because urban and agricultural classes are more closely associated with concentrations of humans that provide more sources for ignition (e.g. Moreira et al. 2001). Nonetheless, despite the increased chance of ignition, urban land and most agricultural classes do not favor the spread of large fires. This is because of the combined effect of a more discontinuous fuel distribution together with intense suppression efforts in areas of high human presence.

Vega-Garcia and Chuvieco (2006) investigated the relationship between local landscapes heterogeneity and wildfire occurrence in Eastern Spain over a 15-year period (1984–1998). They found significant relationships between local spatial pattern analyzed from non-classified remote sensing data and fire occurrence. As expected, fire occurrence, estimated as the probability of burning in the near future, increased where local homogeneity was higher.

Likewise, as in most Mediterranean regions, urban and agricultural lands in Sardinia are subject to a secular process of anthropogenic impact that generates a long-term stratification of heterogeneous patches of limited size that inhibit fire spread.

A notable exception is arable lands, which show a slight, though not significant, selectivity for large fires, mainly because of the illegal practice of straw burning. This tendency is reinforced by the very short fire rotation period (83.14 years) of this land-cover class.

Besides fuel discontinuity, in lands with high human pressure, fire-suppression efforts are also

significant in limiting fire spread. For instance, as in any other cultural landscape, in Sardinia very high priority is given to protection of human settlements whereas less effort is devoted to fire fighting in areas where anthropic presence is negligible (Nunes et al. 2005).

As shown in Table 3, the mean fire size for the largest fires is only 14.68 ha, suggesting that fire suppression is highly effective almost everywhere. This could be explained by the fact that many fires are ignited under moderate weather conditions, a factor that contributes to their suppression at a small size (Keeley et al. 1999).

By contrast, large catastrophic wildfires are usually driven by severe fire weather conditions with high wind speeds; under these conditions the role of landscape structure in determining fire propagation is markedly reduced such that the behavior of very large fires approximates a standard physical percolation model in which the broad-scale cumulative effects of interacting features (terrain, vegetation, etc.) can be effectively modeled by random probability assignments (Caldarelli et al. 2001).

Under these conditions fire suppression techniques are largely ineffective. In Sardinia during 2000–2004 there were three wildfires larger than 1,000 ha. Together, these fires burned 4,372 ha; this was approximately 3.5 times the burnt area in the urban land-cover class during the same period.

Overall, the results obtained emphasize an interesting connection between fire number and mean fire size. As shown by Tables 2 and 3, most urban and agricultural classes that are characterized by high chances of ignition are less likely to be burnt by large fires. At the same time, most natural and semi-natural classes with low chances of ignition are more likely to be burnt by large fires. Is this a general feature of fire behavior? Are there predictable ecological processes underlying this pattern? These are critical questions, and their answers may provide valuable insights into the mutual interactions between landscape structure and fire regimes.

Conclusions

This study highlights a close association between fire incidence and land cover. For most land-cover classes, fire does not occur as expected from a

random null model; rather, it behaves selectively, showing marked preference (or avoidance) in terms of fire number and fire size. Therefore, the fire proneness of a given landscape class should be analyzed keeping the number of expected fires and the mean fire size separate from each other.

From a practical viewpoint, fire agencies need to have effective decision-support tools for quantifying fire risk. Specifically, to improve fire prevention, fire managers need information about the spatial distribution of fires across the landscape (Lasaponara and Lanorte 2007). In this framework, fire selectivity analysis can support fire fighting and reduce damage caused by fires, especially in densely populated regions, areas of high ecological value, etc. The proposed statistical approach is easy to perform on any spatial scale and with any meaningful land use classification scheme providing valuable effects for the development of strategies for fire-risk assessment and fire prevention.

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