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Fifteen years of changes in fire ignition frequency in Sardinia (Italy): A rich-get-richer process

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ABSTRACT

Humans have increasingly been affecting fire regimes through changes in the amount and distribution of ignition energy and fuel load. Within the context of global change, recent studies have shown that changes in demography and land use account for far more variability in shaping fire regimes than climatic variations. The objectives of this study are to analyze temporal trends in fire ignitions in selected land use/land cover (LULC) classes in Sardinia (Italy) over the years 2000–2015, and to assess the role of demographic dynamics from 1971 to 2011 over such changes. We identified the LULC types where annual fire frequency is higher or lower than expected from a null model through a 'fire selectivity index'. Then we analyzed the temporal trend of fire selectivity in all LULC types with linear regressions and tested the role of demographic trends on fire frequency through a two-way contingency table. A general trend of increasing fire occurrence was observed in highly-managed LULC classes, which are mainly located in regions with positive demographic variation; whilst, a decreasing trend of fire occurrence was observed in less human-impacted LULCs, which are preferentially associated to inner regions with negative demographic variation. Results highlight a rich-get-richer process in which anthropogenic LULC classes with highest fire frequency tend to be increasingly selected by fire, whereas in less impacted LULC fire frequency is progressively reduced. The relationship between fire ignitions and demographic processes is of great socio-ecological relevance, because it contributes to clarify the human influence on changing fire regimes.

1. Introduction

The term 'fire regime' refers to the characteristics of fires in a given place over a given time period (Krebs et al., 2010). The most commonly used attribute in the analysis of historical fire regimes is fire frequency (Lutz et al., 2011), being the disturbance frequency a major driver of ecological patterns and processes with profound effects on ecosystems and landscapes (Turner, 2010).

At global scales, climate is the main driver of fires because it controls fire weather (Flannigan et al., 2000) and terrestrial plant productivity, which is the major source of flammable biomass (Pausas and Paula, 2012). At finer scales, changes in fire regimes are mainly driven by human pressure through changes in the amount and distribution of ignition energy and fuel load (Moreno et al., 2014; Fréjaville and Curt, 2017).

A number of authors have studied human-driven changes in fire frequency at global scale (Hantson et al., 2014) and in several terrestrial regions, including Africa (Archibald et al., 2012), the Alpine region (Conedera et al., 2018), and Southern Europe (Bal et al., 2011; Moreira et al., 2011). In the Mediterranean region, human activity is almost the only cause of fire ignition and its role has dramatically increased in the last decades (Bal et al., 2011; Ganteaume et al., 2013; Mateus and Fernandes, 2014; Vilar et al., 2016) to such an extent that anthropogenic activities have vastly expanded the natural spatial and seasonal 'fire niche', overcoming the role of climate (Balch et al., 2017).

Among the main anthropogenic drivers of ignitions, there are the lack of adequate fuel management (Salis et al., 2018), proximity to urban areas (Hammer et al., 2009; Lampin-Maillet et al., 2010; Conedera et al., 2015), distance from roads (Syphard et al., 2007; Narayanaraj and Wimberly 2012, 2013; Satir et al., 2016; Ricotta et al., 2018) and differences in land cover (Nunes et al., 2005; Bajocco and Ricotta, 2008). As shown by several authors, certain land cover classes

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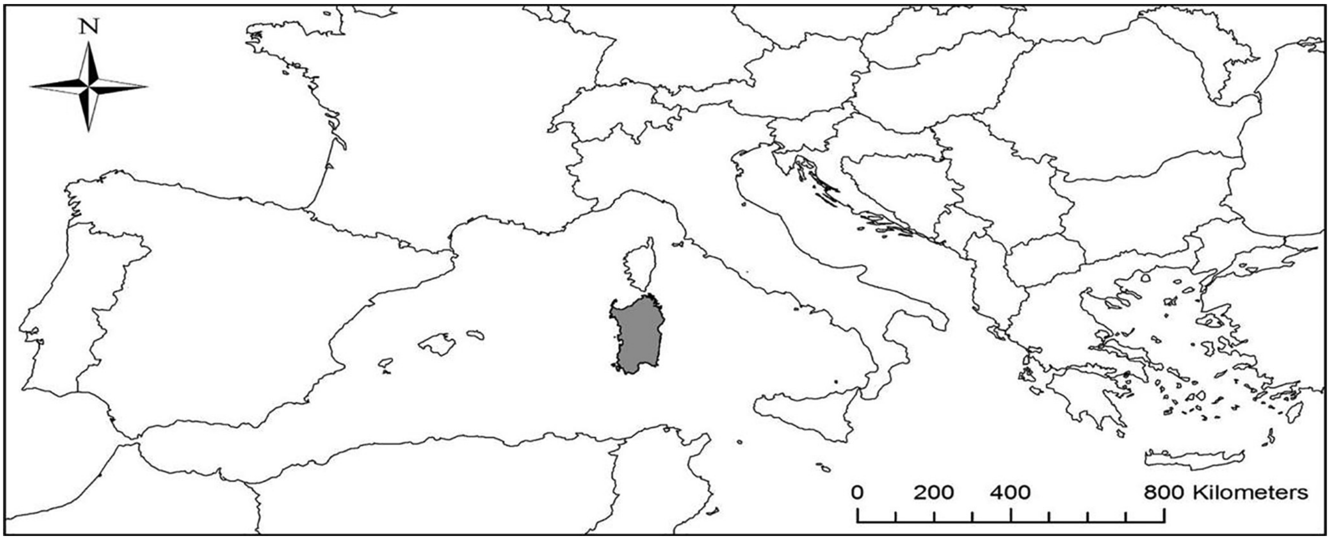

Fig. 1. Location of the study area.

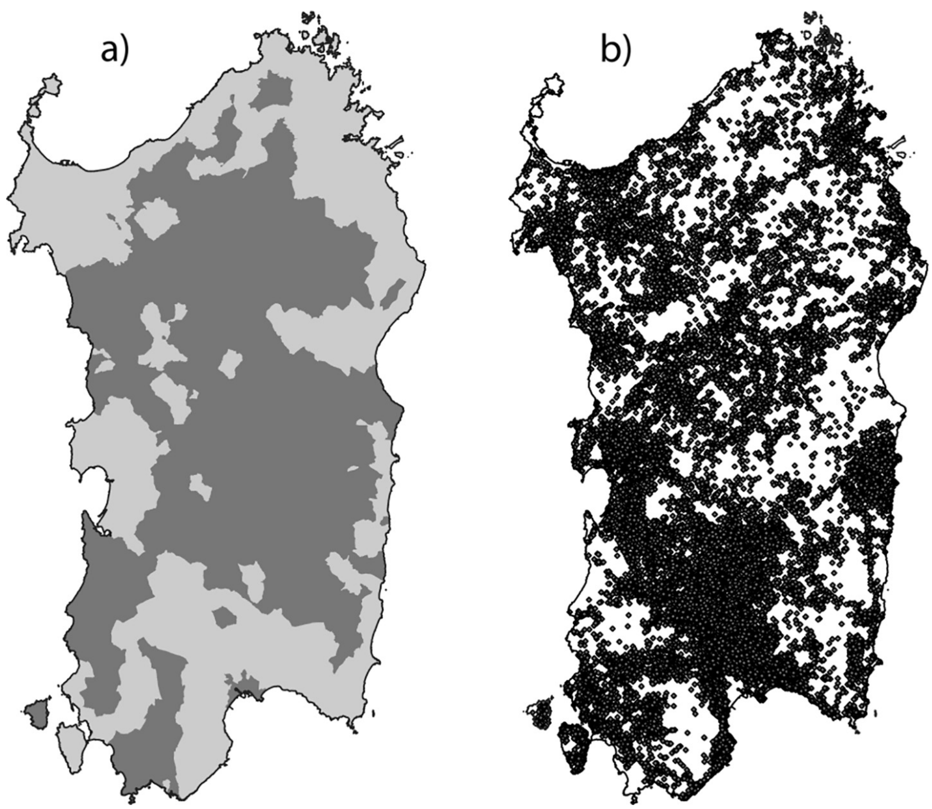

Fig. 2. a) Demographic variation in Sardinia over the time period 1971–2011. Areas with positive demographic variation are shown in light grey; areas with negative demographic variation are in dark grey; b) Spatial distribution of fire events over the period 2000–2015.

Table 1
LULC types used to analyze changes in annual fire frequency in Sardinia over the time period 2000–2015.

LULC types	Area (ha)	Proportion (%)
Urban areas	59302.27	2.893
Arable land	510417.64	24.901
Permanent crops	47449.90	2.315
Mixed agriculture	417125.18	20.350
Forests	346677.00	16.913
Grasslands	60547.80	2.954
Maquis	608234.49	29.674

are more fire-prone than others, depending on fuel load, structure, spatial continuity and on human activities. As a consequence, a high frequency of fire ignitions in more human-impacted land uses with high availability of anthropogenic ignition energy is usually observed (Moreira et al., 2011; Nunes et al., 2005; Bajocco and Ricotta, 2008; Barros and Pereira, 2014).

In addition, in the last decades most Mediterranean landscapes have been greatly modified by the 'rural exodus syndrome' *sensu* Hill et al. (2008), the widespread land abandonment of large areas of southern Europe and the strong concentration of population along the coast where tourism, urban development and industry prevail (Hill et al.,

Table 2
Annual number of fire ignitions in each LULC type over the time period 2000–2015, together with the corresponding selectivity values (in brackets).

Year	Urban areas	Arable land	Permanent crops	Mixed agriculture	Forests	Grasslands	Maquis	Total 2000–2015
2000	126 (2.466)	557 (1.267)	78 (1.908)	525 (1.461)	145 (0.485)	33 (0.633)	302 (0.576)	1766
2001	196 (2.375)	855 (1.203)	144 (2.180)	858 (1.478)	213 (0.441)	65 (0.771)	522 (0.617)	2853
2002	139 (2.958)	601 (1.486)	84 (2.234)	481 (1.455)	96 (0.350)	22 (0.459)	201 (0.417)	1624
2003	180 (2.459)	961 (1.525)	138 (2.356)	721 (1.400)	150 (0.351)	34 (0.455)	346 (0.461)	2530
2004	212 (2.715)	1070 (1.592)	147 (2.353)	807 (1.469)	133 (0.291)	38 (0.477)	292 (0.365)	2699
2005	180 (2.431)	1023 (1.605)	161 (2.718)	689 (1.323)	138 (0.319)	24 (0.318)	344 (0.453)	2559
2006	151 (2.744)	691 (1.459)	176 (3.997)	529 (1.367)	93 (0.289)	24 (0.427)	238 (0.422)	1902
2007	231 (2.838)	1051 (1.500)	178 (2.733)	793 (1.385)	140 (0.294)	62 (0.746)	358 (0.429)	2813
2008	159 (2.763)	753 (1.520)	115 (2.498)	562 (1.388)	138 (0.410)	26 (0.443)	236 (0.400)	1989
2009	179 (2.805	887 (1.615)	131 (2.565)	664 (1.479)	97 (0.260)	29 (0.445)	219 (0.335)	2206
2010	224 (2.473)	1512 (1.939)	202 (2.787)	806 (1.265)	98 (0.185)	48 (0.519)	241 (0.259)	3131
2011	164 (2.043)	1097 (1.588)	206 (3.207)	798 (1.413)	133 (0.283)	63 (0.769)	314 (0.381)	2775
2012	148 (2.316)	955 (1.736)	143 (2.796)	633 (1.408)	81 (0.217)	33 (0.506)	216 (0.330)	2209
2013	123 (2.422)	764 (1.748)	152 (3.741)	437 (1.224)	75 (0.253)	23 (0.444)	181 (0.348)	1755
2014	351 (3.015)	1962 (1.958)	240 (2.576)	1134 (1.385)	68 (0.100	42 (0.353)	227 (0.190)	4024
2015	277 (3.437)	1353 (1.950)	187 (2.900)	733 (1.293)	74 (0.157)	21 (0.255)	141 (0.171)	2786
Total LULC	3040 (2.652)	16,092 (1.631)	2482 (2.706)	11,170 (1.385)	1872 (0.279)	587 (0.502)	4378 (0.372)	39,621

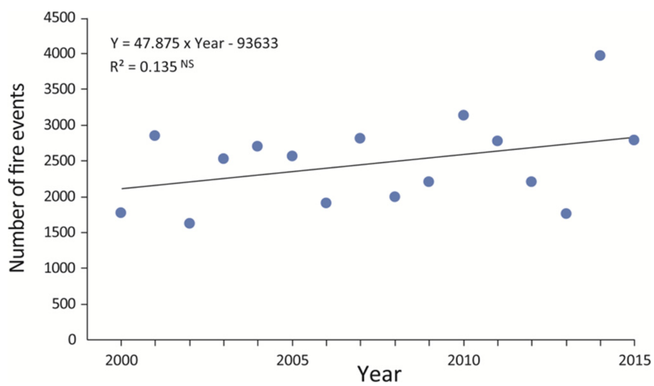

Fig. 3. Temporal trend of total fire events over the 2000–2015 time period. NS = not significant at $p < 0.05$.

2008; Moreira et al., 2011). This abandonment is caused by the inland low economic productivity and is often associated with rural population decline due to emigration and ageing (Moreira et al., 2011; Bajocco et al., 2018).

Several authors have studied the changes in fire frequency in relation to changes in land use. For review, see Moreira et al. (2011) and references therein. Land use/land cover (LULC) changes are related to fire ignition risk due to variations in human impact and anthropogenic ignition energy. Increased fire frequency is expected where LULC changes have determined an increase in human impact, such as those resulting from increased urbanization at the urban-forest interface (Lampin-Maillet et al., 2010), or from intensification of agricultural practices (Moreira et al., 2011). Conversely, fire frequency will decrease in other LULC changes when associated with both land abandonment and reduced availability of anthropogenic ignition energy (Ricotta et al., 2012).

Nonetheless, under changing socio-economic and environmental conditions, possibly stable LULC types are also subject to changes in fire frequency depending on their geographical location with respect to the main demographic fluxes. In this perspective, the key objectives of this study are (i) detecting changes in fire frequency in selected LULC types that occurred in Sardinia (Italy) over the 2000–2015 time period, and (ii) assessing the role of demographic dynamics over such changes. The association between fire ignitions in different LULC types and populating/depopulating processes is of great socio-ecological interest because it allows clarifying the role of anthropogenic drivers in the spatial and temporal distribution of changing fire regimes.

2. Material and methods

2.1. Study area

Sardinia is one of the largest islands in the Mediterranean Sea, covering 24090 km^2 (Fig. 1).

The island is mainly characterized by hilly topography and extreme morphological heterogeneity, with a high environmental diversity and a long history of human presence. Sardinia's climate is typically Mediterranean with approximately 300 days of sunshine, hot and dry summers and mild and rainy winters. Average annual rainfalls range from less than 500 mm in the coastal areas to more than 1200 mm in the inner mountainous regions (Salis et al., 2014). Mean annual temperature ranges from 11 to 17 °C. Urban areas cover 3% of the island. Land use along the coast and the more level areas is dominated by agriculture that covers about 45% of the island. In the interior areas, forest stands combined with pastures and shrublands prevail (Bajocco and Ricotta, 2008).

2.2. Data

The demographic census in Italy takes place every ten years, and the first digital data were recorded on 1971. Therefore, for the demographic analysis, we considered 1971 as the initial stage. The population density in 1971 and 2011 was extracted for each of the 377 municipalities of Sardinia from the National Census of Population and Households (http://dati-censimentopopolazione.istat.it/Index.aspx). We next identified the municipalities either experiencing a demographic increase or decrease in the time period 1971–2011 (Fig. 2).

Based on the wildfire database recorded by the regional Forest Service from 2000 to 2015, we compiled a 16-year fire history of Sardinia with geographic coordinates associated with each ignition point (Fig. 2). To analyze the relationship between fires and land cover, we used a land-cover map derived from CORINE land-cover (CLC) data of 2000 and 2012. The original CLC classes were aggregated into seven macro-classes homogeneous for the amount and spatial continuity of fuel load (Table 1) that were considered adequate to study fire incidence patterns at the landscape scale (Bajocco and Ricotta, 2008).

Bare soils, wetlands, and water bodies were excluded from the analysis. In order to understand the role of demographic dynamics in shaping fire frequency through time and to avoid variability related to land use changes, we considered only the stable CLC polygons, i.e. those polygons that did not change land use type over the study period.

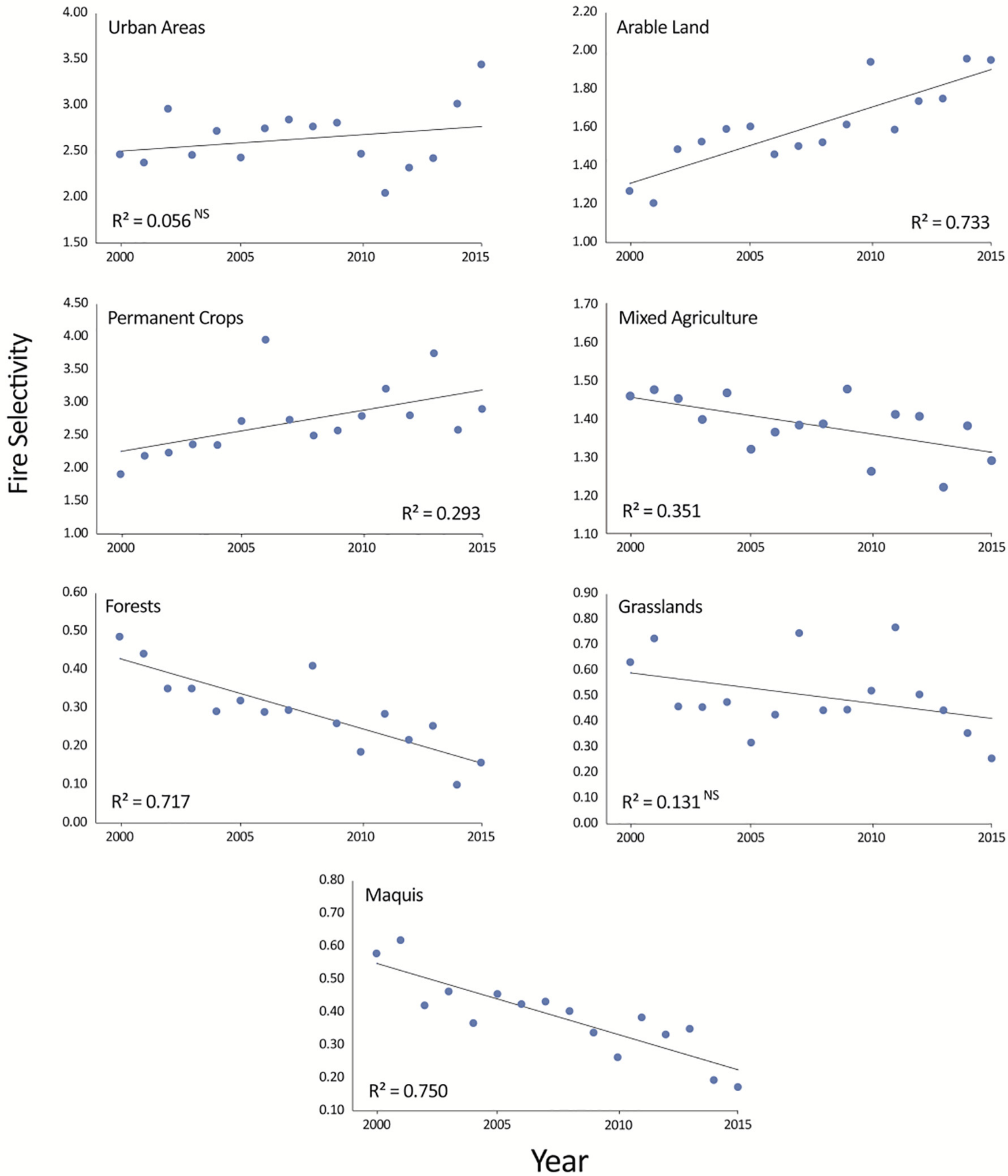

Fig. 4. Temporal trend of the selectivity index by LULC type. NS = not significant at $p < 0.05$.

2.3. Data analysis

To obtain information about the number of fires within each LULC class, the ignition points were overlaid on the land-cover map of Sardinia. First, by means of a regression analysis, we analyzed the temporal trend of all the ignition points recorded in Sardinia during the period 2000–2015. Next, to identify land cover types where annual fire frequency is higher or lower than expected from a null model in which fires are distributed randomly across the LULC classes, a ‘fire selectivity index’ (σ) ranging [0, ∞] was calculated for each year as the proportion of fires in a given LULC class, divided by the relative area of that LULC class in the study site. Values larger than 1 denote LULC classes where ignitions occur more frequently than expected by chance alone; in a sense, according to Bajocco and Ricotta (2008), these LULC classes are ‘preferred’ by fire. Values lower than 1 denote LULC classes ‘avoided’ by fire where ignition is less frequent than expected by chance. The temporal trend of fire selectivity in all LULC types was then computed with linear regressions.

To explore the impact of demographic trends on fire frequency, we finally constructed a two-way contingency table in which the LULC type of each ignition point was associated to either positive or negative demographic variation during the 1971–2011 time period. The actual values of all entries of the contingency table were then compared to a distribution of 9999 random values obtained under the null hypothesis that the different LULC types in Sardinia are not preferentially located in regions of either positive or negative demographic variation. For all ignition points, the association between land use and demographic variation was randomized keeping constant the number of fires in each

Table 3
Contingency table in which the land use types of all fire ignition points are associated to either positive or negative demographic variation at the municipality level over the time period 1971–2011. Bold characters denote positive association between land-use and either positive or negative demographic trends; normal characters denote negative association. All values of the contingency table are significant at $p < 0.05$ (two-tailed test, 9999 permutations).

LULC types	Demographic variation	
	Positive	Negative
Urban areas	**1759**	1281
Arable land	**9659**	6433
Permanent crops	**1970**	512
Mixed agriculture	6082	**5088**
Forests	592	**1280**
Grasslands	207	**380**
Maquis	1707	**2671**

LULC class.

3. Results

In Sardinia, in good agreement with previous works (e.g. Bajocco and Ricotta, 2008; Ricotta et al., 2018), all LULC classes with high anthropogenic pressure, such as urban areas, arable lands, permanent crops and mixed agriculture, are characterized by selectivity values larger than 1, meaning that these classes are positively selected by fire. On the other hand, forests, grasslands and maquis all show selectivity values lower than 1, denoting that in these classes the number of ignitions is generally lower than expected by chance alone (Table 2).

During the period 2000–2015, the stable areas of Sardinia that did not change land use type experienced 39,621 wildfires (Table 2). As shown in Fig. 3, the temporal regression analysis for the whole study area did not show any type of significant trend in the annual number of fire ignitions.

To the contrary, the results of the temporal regression analysis of the σ values in each LULC type show a clear increasing or decreasing trend, depending on the specific land cover type (Fig. 4): arable land and permanent crops show a significantly increasing trend in fire selectivity through the years, while mixed agriculture, maquis and forests are characterized by a significantly decreasing trend over the analyzed time period. Urban areas and grasslands do not show any significant trend.

The analysis of the degree of association between the LULC classes and the 1971–2011 demographic trends (Table 3) show that the fire ignitions in urban areas, arable lands and permanent crops are significantly associated to regions with positive demographic variation, which are mainly located along the coasts and in the more level portions of the island; whereas, the fire ignitions in forests, grasslands, maquis, and mixed agriculture are preferentially associated to inner depopulating regions. The same analysis was carried out starting from 1981 or 1991 and confirmed these results in sign and strength (data not shown here).

4. Discussion

Since the advent of the Anthropocene, human activities have increasingly been affecting fire regimes through population growth, settlements, land use changes, and fire management (McWethy et al., 2010; Roebroeks and Villa, 2011). Within the framework of global change, recent modelling studies have shown that, at a regional scale, changes in demography and land use account for far more variability in shaping future fire regimes than does climate variations (Moritz et al., 2012; Bryant and Westerling, 2014).

In this context, our work contributes to the understanding of fire behavior through time, analyzing the temporal trends of fire selectivity towards different land cover types and testing the role of anthropogenic pressure. Results of the linear regression analysis demonstrated that, taken as a whole, the wildfires that occurred in Sardinia in 2000–2015 did not experience any significant temporal tendency, notwithstanding the well-known current increase in fire-prone climatic conditions (e.g. Dennison et al., 2014; Moreno et al., 2014; Wang et al., 2015; Westerling, 2016). However, looking at the different land use types separately, wildfires showed significant selectivity trends through time. Therefore, while the total annual number of fires in Sardinia remained more or less stable in 2000–2015, the proportions of fires associated to the different LULC types significantly changed through time. In detail, maquis and forests show a decreasing trend in fire selectivity through time. On the contrary, agricultural land uses, where fire is a traditional management practice, tend to be increasingly affected by fires. A notable exception is represented by the class 'mixed agriculture', which is a transitional LULC type, often located at the forest edge. Overall, such evidences suggest that there is a general pattern of increasing fire occurrence in highly-managed land use classes and decreasing occurrence in scarcely-managed categories, which is free from any climatic change forcing. Since the analysis focused solely on stable portions of the landscape, thus excluding any changes in fire frequency induced by changes in land use, the observed pattern is most likely related to variations in demographic trends and hence to changes in human pressure.

Human population dynamics are long-term processes and their socio-ecological feedbacks tend to be delayed in time (Lafuite and Loreau, 2017), so in order to study their effects on environmental processes, a large time span is needed. The analysis of the degree of association between the LULC classes and the demographic trends over the last 40 years showed that the agricultural land uses which experienced a significant increasing trend in fire occurrence are mainly located in areas with positive demographic variation. A notable exception is represented by the class 'mixed agriculture', which is often located on marginal agricultural lands that are usually subject to negative demographic trends (Bajocco et al., 2010). Accordingly, for this LULC class, the reduction of anthropogenic pressure coupled with the progressive abandonment of traditional agricultural practices results in a decreasing trend in fire selectivity trough time. In contrast, maquis and forests, which are generally characterized by decreasing fire occurrence, are mainly located in interior and less economically productive areas with negative demographic variation and hence reduced availability of anthropogenic ignition energy. Particularly for forests, a progressively decreasing human impact also leads to an increasing degree of canopy closure, giving rise to a less flammable fuel bed with high moisture content (Fernandes et al., 2010).

These results highlight a rich-get-richer process in which the anthropogenic LULC types with highest fire selectivity tend to be increasingly selected by fire: the more the population grows, the more increases the available fire ignition energy. On the other hand, in LULC types which are preferentially located in depopulating areas, the fire ignition sources are progressively reduced, thus leading to decreasing fire selectivity. However, depopulation and abandonment of marginal areas, while reducing fire ignitions in the short term, potentially increase the accumulation of fuel and thus the risk of future large fires, a phenomenon known as the 'Yellowstone effect' (Malamud et al., 1998).

To conclude, especially in densely populated areas, the quantification of fire ignition risk in different LULC types provides valuable information for supporting firefighting and prevention programs. Under changing environmental scenarios, a thorough knowledge of landscape changes and its relationship with demographic dynamics is a key point in order to understand the role of humans in the whole spectrum of fire behavior.

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