Progress in Physical Geography
35(1) 3–18

DOI: 10.1177/0309133310380768
ppg.sagepub.com
SAGE

Land degradation versus fire: A spiral process?

Sofia Bajocco
Council for Research in Agriculture – Unit of Climatology and Meteorology applied to Agriculture (CRA-CMA), Italy

Luca Salvati
'Sapienza' University of Rome, Italy

Carlo Ricotta
'Sapienza' University of Rome, Italy

Abstract

Originally associated to arid regions, vulnerability to land degradation (LD) has rapidly spread in temperate areas, such as the Mediterranean basin. In this region LD increased in the last years due to worsening climate conditions, land-cover changes, soil erosion and anthropogenic pressures. Increasing land vulnerability is mutually linked with an increasing risk of disturbance propagation: the spatio-temporal distribution of areas with different degrees of LD determines different dynamic patterns of the disturbance; in turn, LD is strongly affected by the disturbance occurrence regime, which alters the status quality of a given territory. These considerations invite a comparison between vulnerability to LD and fire occurrence, since historically, in the Mediterranean areas, fire represents one of the main disturbance sources, which is mostly human-induced and with a strong seasonality pattern. Under certain conditions, LD may create conducive conditions for fire to thrive that in turn if repeated may alter the quality status of a landscape, setting the interested area into a LD-fire feedback dynamic. The aim of this paper is to analyse the relationship between fire incidence and LD and their potential feedbacks in Sardinia during two reference periods, 1990 and 2000. Results indicated that in areas already affected by high LD vulnerability there is a sort of LD-fire spiralling connection that can be seen as a 'mutual early-warning system' with strong implications on fire prevention strategies and landscape quality status monitoring.

Keywords

fire, Italy, land degradation, land use, Sardinia, vulnerability

I Introduction

The international definition of the United Nations Convention to Combat Desertification (see http://www.unccd.int/convention/text/convention.php), describes 'land degradation' as a 'reduction or loss of the biological and economic productivity' (MEA, 2005a, 2005b) resulting from land uses (mismanagement), or a combination of processes, such as soil erosion, deterioration of soil properties, and long-term loss of natural vegetation (Giordano and Marini, 2008). Land degradation (LD) is hence an interactive

Corresponding author:
Sofia Bajocco, Council for Research in Agriculture – Unit of Climatology and Meteorology applied to Agriculture (CRA-CMA), Via del Caravita 7a, 00186 Rome, Italy
Email: sofia.bajocco@entecra.it

process involving multiple factors, among which climate and land use play a significant role (Geist and Lambin, 2004; Lambin et al., 2001; Reynolds and Stafford Smith, 2002). Particularly in the Mediterranean regions, the biophysical and socio-economic aspects represent the main factors impacting on land vulnerability, and their interaction may become extremely complex through space and time, resulting in typical LD patterns. Here, LD is considered as a process occurring not only in semi-natural areas, but also in agricultural and peri-urban areas. For instance, other than soil erosion, the major drivers of LD in the Mediterranean basin are soil sealing, soil compaction due to agricultural intensification, soil salinization, and soil contamination due to industrial activities (Montanarella, 2007). All these phenomena occur in agricultural and peri-urban lands other than in natural or semi-natural areas.

In order to identify and foresee the local distribution of vulnerable areas, understanding of the spatio-temporal trends (rather than of the actual status) of LD represents a key issue both from the ecological and policy point of view (Dube, 2007). Based on these considerations, the working hypothesis of this paper is that LD, determining the sensitivity level of an area, directly influences disturbance dynamics, and that the spatio-temporal distribution of areas with different degrees of LD determines different occurrence patterns of the disturbance. In turn, LD is strongly affected by the disturbance occurrence regime, that alters the status quality of a given territory. This mutual interaction between disturbance regimes and landscape structure may become complex, resulting in temporally and spatially varying patterns (Lloret et al., 2002; Roberts, 1996).

Historically, in the Mediterranean area fire represents one of the main disturbance sources and more than the 90% of all fires occurred are human-induced. Furthermore, the strong seasonality, with wet periods, which allow fuel to accumulate, and dry periods, providing favourable 'risk' conditions, increases the fire-proneness of these areas (Beverly and Martell, 2005; Keeley and Rundel, 2005; Shakesby et al., 2007).

The importance of fire in shaping ecological processes has long been recognized (Frost and Robertson, 1987; Goldammer and de Ronde, 2004; Pyne et al., 1996). While the ecological role of fire is well documented, its broader role in environmental processes and resulting feedbacks has until now received limited attention (Gonzalez-Perez et al., 2004; Pyne et al., 1996; Van Wilgen et al., 1997). Recent work has shown that in addition to its known ecological dimensions, fire is also an important land use tool, a growing global hazard and a factor involved in landscape processes with feedbacks on LD (Dube, 2007; Fiorucci et al., 2007; Goldammer and de Ronde, 2004).

Changes in LD patterns are likely to modify the susceptibility to fire of an area; *vice versa* high fire occurrence may alter its land quality status. This complex interplay between fire and LD may be further enhanced under climate and land use change scenarios.

In Mediterranean areas, fire is a recurrent phenomenon and under natural conditions fire maintains the dynamic equilibrium responsible for high biodiversity; but repeated and severe fires can seriously damage ecosystems. Frequent and more intense fires reduce the vegetation cover and biomass of an area, affecting the productive soil layer which leads to soil exposure to meteorological agents (Pérez-Cabello et al., 2010), physical and chemical soil impoverishment (Gimeno-García et al., 2000; Larchevêque et al., 2005), change in species composition and vegetation structure, loss of the seed bank of perennial plants, and increase of fast-growing invader species (Dube, 2007). These effects have strong implications on biodiversity decline, soil erosion, general productivity of the landscape, and therefore on the LD of the interested area (Shakesby et al., 2007).

On the other hand, degraded areas appears to be more prone to fire occurrence than non-

Figure 1. Location of the study area

degraded ones (Kyereh et al., 2006). In particular, in Mediterranean regions, degraded areas are mainly characterized by annual herbaceous and shrubby plant species; these kinds of vegetation are extremely fire-susceptible due to their low moisture content and the easily flammable fuel load (Pellizzaro et al., 2005). Furthermore, degraded areas are located in both semi-natural areas as well as in agricultural lands and in the wildland-urban interface where the high human presence determines a higher probability of ignition sources and hence of fire occurrence (Bajocco and Ricotta, 2008).

This paper aims at verifying the existence of a feedback between fire incidence and LD in Sardinia, a typically Mediterranean region highly affected by fire. Does high fire occurrence determine increase in LD sensitivity? Does increase in LD sensitivity determine high fire occurrence? The objectives are hence, on one hand, to quantify how LD influences fire incidence patterns in space and time, and, on the other hand, to verify to what extent the frequent burning of an area is linked with its LD trend. Results demonstrated the existence of LD-fire feedback dynamics that works as a 'mutual early-warning system' with strong implications on fire prevention strategies and landscape quality status monitoring.

II Material and methods

1 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 km^2 (Figure 1). Sardinia is characterized by a complex physical geography, with a prevalently hilly topography and extreme heterogeneity in geological and morphological features, with a wide variety of biotopes and a long history of human presence. The highest elevation is 1834 m; average elevation is 338 m. The climate of Sardinia is predominantly Mediterranean with 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 900 mm in the inner mountainous regions. Mean annual temperature ranges from 11°C to 17°C.

Land cover along the coast and the main river valleys is dominated by sclerophyllous shrubs, thermomediterranean *Quercus ilex* forests, and agricultural lands that cover about 45% of the study area. Most urban areas of Sardinia are located in the coastal zone. In the interior areas, forest stands combined with pastures and shrublands prevail. The principal forest formations include mesomediterranean *Quercus ilex* and *Q. suber* forests. At higher elevations the sclerophyllous oak forests merge with broadleaved forests of *Quercus pubescens*.

Sardinia is characterized by a strong incidence of fires, mainly during the driest summer months, with a mean of about 2000 events per year. The intense wildfire activity (Bajocco and Ricotta, 2008), together with grazing pressure (D'Angelo

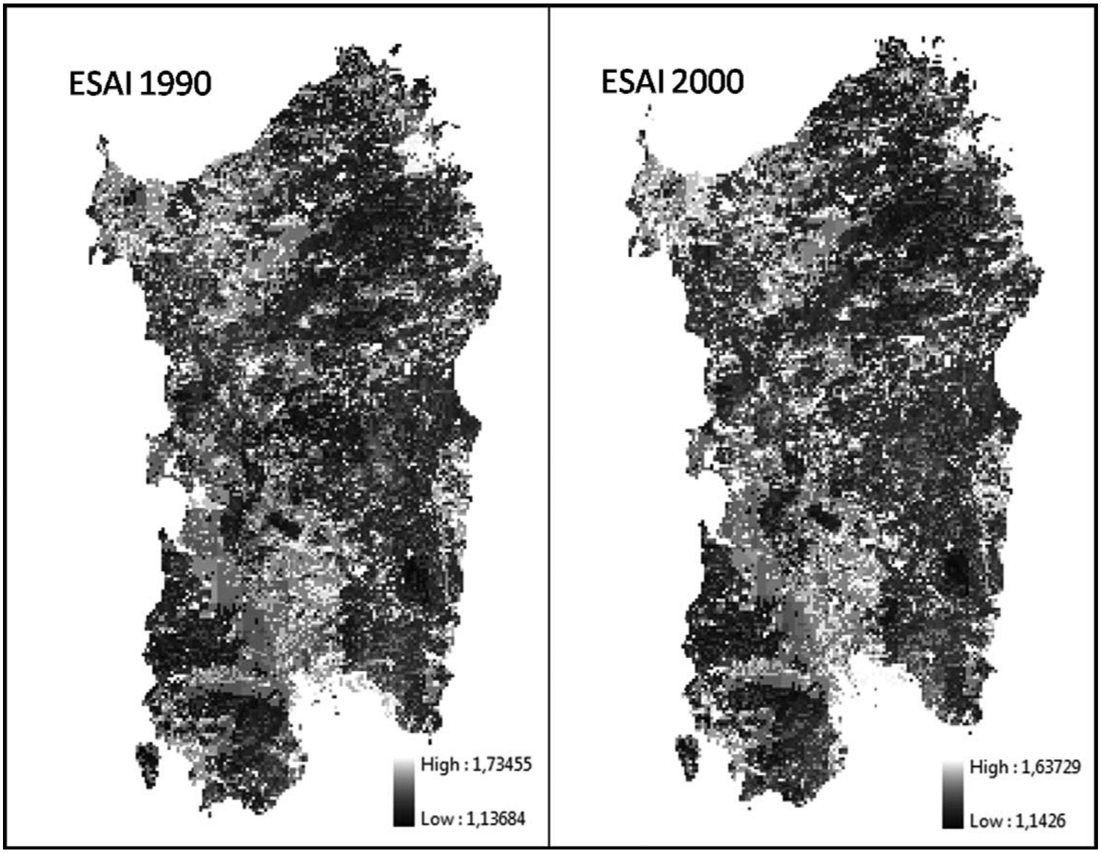

Figure 2. ESAI distribution maps in 1990 (left) and 2000 (right)

et al., 2000; Enne et al., 2002), local droughts (Fiori et al., 2004), mismanagement and salinization of groundwater resources (Santini et al., 2010), deforestation, land overexploitation and abandonment (Giordano and Marini, 2008) represent the key factors causing LD in Sardinia. For a more detailed description of the LD processes in the study area, see Motroni et al. (2009).

2 Land degradation sensitivity map

According to the Environmental Sensitivity Areas (ESA) framework (Brandt et al., 2003), LD sensitivity maps were produced for 1990 and 2000 (Figure 2). The ESA procedure was implemented on the framework of the Medalus project on the Mediterranean LD and rapidly became a standard for several international, interdisciplinary research projects which carried out extensive evaluations of LD sensitivity (Brandt et al., 2003). This framework was applied at both the regional and local scale in several Mediterranean areas (Portugal, Spain, Italy, Greece) showing complex and locally differentiated environmental processes. The procedure is quite feasible and able to integrate indicators from different data sources. It was extensively validated in the field at several target sites (Kosmas et al., 1999) by analysing the correlation between the ESAI and indicators of soil quality and physical degradation (Basso et al., 2000; Lavado Contador et al., 2009).

The methodology is based on more than 10 variables covering different themes, including the geological, topographical and climatic conditions, the anthropogenic pressure, and the typical features of land cover for Mediterranean Europe. Statistical analysis was performed for each variable in order to define (1) the correlation of the variable to the stage of LD, (2) the correlations within the data matrix, and (3) the contribution of each variable to the estimation of land sensitivity (Basso et al., 2000). To each variable a set of sensitivity scores was assigned. Scores were derived from the statistical analysis and from additional information gathered from the available literature (Kosmas et al., 2000a, 2000b). A sensitivity analysis and a focus group analysis were finally carried out in order to indicate the most valid, low-cost and efficient set of key variables and scores by theme (Kosmas et al., 1999). For each theme, a quality indicator was calculated by averaging the sensitivity scores of the selected variables. The variables selected to create the ESAI maps (Table 1) refer to four themes: climate, soil, vegetation, and human pressure (see Basso et al., 2000; Lavado Contador et al., 2009).

Climate quality was described in the ESA framework by the average annual rainfall rate (RAI), aridity index (ARI) (defined as the ratio between rainfall and reference evapotranspiration, both measured over a long term) and aspect (ASP). The reference evapotranspiration rate was calculated using the Penman-Monteith formula. These indicators were calculated using basic information available in the National Agro-meteorological Database of the Italian Ministry of Agriculture (Salvati et al., 2008). Two analysis periods were selected: 1961–1990 and 1971–2000.

Soil data were obtained from the soil quality map produced in the framework of the DISMED project (Brandt, 2005) and derived from the European Soil Database (ESD). According to the standard ESA model, variables including soil texture (TEX), depth (DEP), slope (SLO), drainage (DRA), rock fragments (FRA) and parent material (PAR) were used (Kosmas et al., 2000a, 2000b). This information was supplemented by ancillary data (see Salvati and Zitti, 2009).

The impact of vegetation on LD was quantified according to Kosmas et al. (2000a): a weight was attributed to each land use category in order to obtain a classification of the territory based on the different level of sensitivity of its vegetation (Brandt et al., 2003) in terms of fire proneness (FIR), protection from soil erosion (ERO), drought resistance (DRO), and vegetation cover (PLA). Such indicators were obtained from Corine Land Cover (CLC) cartography in 1990 and 2000 (Basso et al., 2000).

Finally, the impact of human pressure on LD was assessed as a result of processes such as the increase of population density and the intensification of agriculture (eg, Otto et al., 2007). The population density (DEN) was measured at the municipal level in 1981, 1991 and 2001 on the basis of the National Census of Population (Salvati and Zitti, 2007). The annual demographic growth rate (GRW) calculated for defined time horizons (1981–1991 and 1991–2001) was computed at the same geographical scale. An index of agricultural intensification (AGR) was further obtained from the CLC maps of 1990 and 2000. According to Kosmas et al. (2000a), a weight was attributed to each land use in order to obtain a classification of the territory based on crop intensity (Salvati et al., 2007).

Four thematic indicators, quantifying the environmental quality in terms of climate (Climate Quality Index, CQI), soil (Soil Quality Index, SQI), vegetation (Vegetation Quality Index, VQI) and land management (Land Management Quality Index, MQI), were estimated as the geometric mean of the different scores for each involved variable as follows:

$$CQI_{i,j} = (RAI_{i,j} * ARI_{i,j} * ASP_{i,j})^{1/3}$$

$$SQI_{i,j} = (TEX_{i,j} * DEP_{i,j} * PAR_{i,j} * FRA_{i,j} * DRA_{i,j} * SLO_{i,j})^{1/6}$$

$$VQI_{i,j} = (FIR_{i,j} * ERO_{i,j} * DRO_{i,j} * PLA_{i,j})^{1/4}$$

$$MQI_{i,j} = (DEN_{i,j} * GRW_{i,j} * AGR_{i,j})^{1/3}$$

The scores of each thematic indicator ranges from 1 (the lowest contribution to land

Table 1. Variables used in ESAI, units of measure and statistical sources

Theme	Variable	Scale	Unit of measure	Source
Soil quality	Soil texture	1:250,000	Sensitivity class	Ministry of Agriculture, European soil database
	Soil depth	1:250,000	mm	Ministry of Agriculture, European soil database
	Parent material	1:250,000	Sensitivity class	Ministry of Agriculture, European soil database
	Rock fragments	1:250,000	Sensitivity class	Ministry of Agriculture, European soil database
	Drainage	1:250,000	Sensitivity class	Ministry of Agriculture, European soil database
	Slope	Raster 250 x 250 m pixel size	%	Ministry of Environment
Climate quality	Annual mean rainfall rate	1:400,000	mm	Meteorological statistics
	Aridity index	1:400,000	mm/mm	Meteorological statistics
	Aspect	Raster 250 x 250 m pixel size	Angle	Ministry of Environment
Vegetation quality	Fire risk	1:100,000	Sensitivity class	Corine Land Cover
	Erosion protection	1:100,000	Sensitivity class	Corine Land Cover
	Drought resistance	1:100,000	Sensitivity class	Corine Land Cover
	Vegetation cover	1:100,000	Sensitivity class	Corine Land Cover
Land management quality	Population density	1:500,000	People km^{-2}	Census of Household
	Population growth rate	1:500,000	%	Census of Household
	Agricultural intensity	1:100,000	Sensitivity class	Corine Land Cover

sensitivity to degradation) to 2 (the highest contribution to sensitivity to degradation). ESAI was subsequently estimated in each i-th spatial unit and j-th year as the geometric mean of the four partial indicators (Basso et al., 2000) as follows:

$$ESAI_{i,j} = (SQI_{i,j}*CQI_{i,j}*VQI_{i,j}*MQI_{i,j})^{1/4}$$

The ESAI score ranges from 1 (the lowest land sensitivity to degradation) to 2 (the highest sensitivity to degradation). Within this range, eight classes of land sensitivity were identified (Table 2) in accordance with Basso et al. (2000) and Brandt et al. (2003). The environmental significance of these thresholds was successfully tested by Lavado Contador et al. (2009). Unclassified cells were excluded from further analysis. According to Lavado Contador et al. (2009), in order to make the spatial calculations, all the variables were digitized in raster format at 250 x 250 m pixel size, corresponding to the minimum pixel size of the digital terrain model used for slope and aspect determination. Over the entire investigated area, the average (and coefficient of variation) ESAI values were 1.302

Table 2. Classification of the study area in terms of sensitivity to LD

ESAI class	ESAI score	Sensitivity class	Land description (examples)
1 (NA)	<1.17	Not affected	Areas not threatened by LD
2 (P)	1.17 – 1.22	Potentially affected	Areas threatened by LD under significant climate change, if a particular combination of land use is implemented or where off-site impacts will produce severe problems elsewhere
3 (F1) 4 (F2) 5 (F3)	1.23 – 1.26 1.27 – 1.32 1.33 – 1.37	Fragile	Areas in which any changes in the delicate balance of natural and human activities is likely to bring about LD. As an example, the impact of predicted climate change could affect vegetation cover, intensify soil erosion, and finally shift the level of sensitivity of the area to the 'critical' class. A land use change (eg, a shift towards cereal cultivation on sensitive soils) might produce immediate increase in runoff and soil erosion, and perhaps pesticide and fertilizer pollution downstream
6 (C1) 7 (C2) 8 (C3)	1.38 – 1.41 1.42 – 1.53 >1.53	Critical	Areas already degraded through past misuse, showing a threat to the environment of the surrounding land (eg, badly eroded areas subjected to severe runoff and sediment loss)

Source: Lavado Contador et al. (2009)

(6.6%) and 1.306 (6.3%) in 1990 and 2000, respectively.

3 Forest fire data

Fire data were provided by the Forest Service of Sardinia and contain all the fires recorded from 1995 (no data available before) to 2008 with the geographic (UTM) coordinates of the ignition point and the size.

For the analysis of the relationship between fire and LD, we used two comparable four-year periods of wildfires: 1995–1998 and 2005–2008, adequate to be referred to the ESAI maps produced (Figure 3).

During the 1995–1998 period, 6900 wildfires were registered, that burned totally 43,639.5 ha; during 2005–2008, the total number of fires occurred was 8793 that burned 54,867.8 ha. Firesize ranges from 0.01 ha to 5992 ha during the first time period, and from 0.01 ha to 9029 ha during the second.

In order to verify the representativeness of the fires occurred during the two analysed periods with respect to the whole available fire history, we compared the spatial patterns of 1995–1998 and 2005–2008 fires with the entire data set of 1995–2008 fires across the different Corine Land Cover (CLC) types of the study area. First, for each land cover type we computed the relative density and compared the obtained values. The density of fires on different land cover types appeared similar in the three periods: as an example, in 1995–1998, 2005–2008 and 1995–2008 only about 7% of fires burned in urban and peri-urban areas, while the majority (more than 60%) burned agricultural areas and 30% burned natural and semi-natural lands. Then we computed for the three periods and each land cover type the average nearest-neighbour index (R) as the ratio of the average observed distance from each point in the pattern to its nearest neighbour, to the average distance expected if the pattern were randomly distributed, which depends solely on the density of the pattern being studied. The index R varies from 0.00 for a totally clustered pattern through 1.00 for a random distribution, to a maximum of 2.15 for a completely regularly spaced pattern. The results confirmed the similar degree of clustering

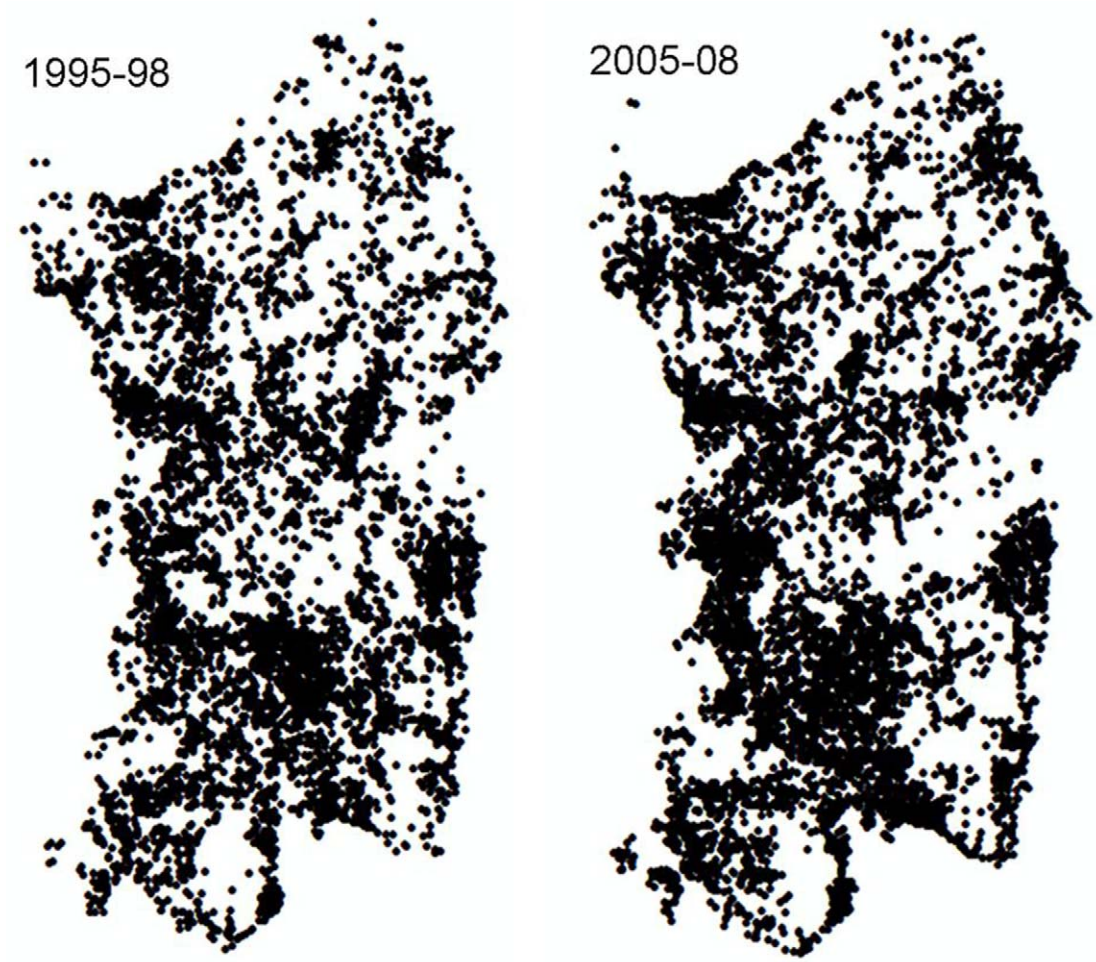

Figure 3. Maps of the ignition points respectively for the fires of 1995–1998 (left) and 2005–2008 (right)

of the examined data sets with respect to the whole fire archive. The R index of both 1995–1998 and 2005–2008 was similar to the R index of 1995–2008: 0.53, 0.51 and 0.50, respectively, in semi-natural areas; 0.50, 0.48 and 0.46 in agricultural lands; and 0.35, 0.32 and 0.29 in peri-urban areas.

4 Statistical analysis

The analysis of the geographic distribution of the fire events has always been an important issue in fire pattern modelling, and now is going to receive more attention for landscape modelling and for fire management and prevention actions. Nowadays many fire management decisions are still exclusively based on fire spread and suppression difficulty. However, as resources are limited, it is important to define priorities among areas, and to areas with higher ignition frequency should be given priority for surveillance (Vasconcelos et al., 2001). The fire ignition probability is hence an essential element in assessing fire occurrence patterns (eg, Finney, 2005; Vasilakos et al. 2007).

This paper focuses on fire ignition rather than on fire size because, in terms of LD sensitivity of a given area, the frequency of fire occurrence in the same land cover type matters more than the dimensions of the fire. Few large fires (as typically occur in Sardinia) weakly impact on the LD status of a territory, while repeated fires, even if small in size, strongly affect the soil and vegetation quality of the burned territory.

In order to quantify the relationship between the different levels of LD sensitivity and the fire ignition patterns, we used the 'fire selectivity' approach proposed by Moreira et al. (2001) that relates landscape composition and fire proneness. We tested the proneness of the different ESAI classes to fire in terms of number of fires; ie, we identified the LD sensitivity classes where the fires are more or less than expected by a random null model (Bajocco and Ricotta, 2008).

To determine whether the number of fires in the examined ESAI classes is significantly different from random, we constructed the following Monte Carlo simulation comparing the fires of 1995–1998 with the ESAI map of 1990, and the fires of 2005–2008 with the ESAI map of 2000: all fires were randomly reassigned to the land sensitivity classes of the corresponding map, such that the probability of assignment of each fire to a given ESAI class was kept equal to the relative extension 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 ESAI class and the relative extension of each class within the analysed landscape (Bajocco and Ricotta, 2008). Therefore we compared, for each four-year period, the actual number of fires in each ESAI class with the results of 999 random simulations. For each ESAI 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.

We then analysed the fire behaviour in relationship with the LD dynamics of the study area. The hypothesis to be tested was if there is a feedback connection between LD sensitivity and fire; that is, on one hand, if LD sensitivity increased where 'past' fires (1995–1998) occurred, and, on the other, if 'future' fires (2005–2008) occurred preferentially where LD sensitivity increased.

We hence performed a change detection (CD) analysis and found the cells that, in the decade going from 1990 to 2000, have improved, remained stable, or worsened in terms of LD sensitivity. The CD analysis produced the transition matrix of Table 4.

In particular, the analysis focused on the 'changed' cells only, without considering the stable cells. On the basis of the previous 'selectivity' analysis results (see the findings illustrated in the Results section and Table 3), considering the cells transition between (inter-) and within (intra-) the two fire-proneness groups of ESAI classes, we derived six CD-ESAI classes as follows:

- class *ab*W: those cells belonging to classes 1–4 (group *a*) in 1990 that worsened, turning into classes 5-8 (group *b*) in 2000;
- class *ab*I: those cells belonging to classes 5–8 (group *b*) in 1990 that improved, turning into classes 1-4 (group *a*) in 2000;
- class *aa*W: those cells belonging to classes 1–4 (group *a*) in 1990 that worsened in 2000, but did not pass in group *b*;
- class *aa*I: those cells belonging to classes 1–4 (group *a*) in 1990 that improved in 2000;
- class *bb*W: those cells belonging to classes 5–8 (group *b*) in 1990 that worsened in 2000;
- class *bb*I: those cells belonging to classes 5–8 (group *b*) in 1990 that improved in 2000, but did not pass in group *a*.

To determine whether the fire number in the examined CD-ESAI classes is significantly different from random, we led the same randomization test as before. We performed the analysis both with the 1995–1998 and 2005–2008 fires, in order to test if the cells changed

Table 3. Selectivity of 1995–1998 fires versus ESAI 1990 and of 2005–2008 fires versus ESAI 2000 in terms of number of events. Lower and upper limits of the Monte Carlo simulations are also shown. Italic: values lower than expected from a random null model, $p < 0.001$; bold: values higher than expected from a random null model, $p < 0.001$.

		1995–1998 fires versus ESAI 1990				2005–2008 fires versus ESAI 2000			
	ESAI classes	Class area (km^2)	Number of fires	Lower limit	Upper limit	Class area (km^2)	Number of fires	Lower limit	Upper limit
Group *a*	1	247	*58*	48	102	105	*25*	24	65
	2	3965	*1 007*	1093	1335	3059	*885*	1107	1310
	3	4784	*887*	1355	1618	5485	*1 165*	2013	2290
	4	4846	*1 223*	1381	1597	4787	*1 274*	1780	2008
Group *b*	5	3982	**1 645**	1138	1327	4285	**2 421**	1595	1844
	6	2480	**953**	671	852	2147	**1 296**	744	930
	7	1951	**1 040**	537	675	2217	**1 623**	799	993
	8	168	**87**	34	71	91	**104**	18	55
	Total	22423	6 900			22276	8 793		

Table 4. Transition matrix of the cells from ESAI 1990 to ESAI 2000 map. In dark grey, the cells that passed from group *a* to group *b* and *vice versa* (inter-group changes); in light grey, the cells that changed remaining in the same group (intra-group changes), either from *a* to *a*, or from *b* to *b*. Cells that passed from lower to higher ESAI classes are in bold; cells that passed from higher to lower ESAI classes are in italic.

		ESAI 1990								
		CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5	CLASS 6	CLASS 7	CLASS 8	Class Total
ESAI 2000	CLASS 1	47	*23*	*23*	*9*	*2*	*1*	*0*	*0*	105
	CLASS 2	**119**	2044	*446*	*326*	*77*	*28*	*7*	*1*	3048
	CLASS 3	**47**	**1280**	2788	*1025*	*187*	*112*	*18*	*0*	5457
	CLASS 4	**27**	**495**	**1262**	2289	*450*	*155*	*74*	*4*	4756
	CLASS 5	**1**	**70**	**207**	**948**	2223	*449*	*276*	*15*	4189
	CLASS 6	**0**	**1**	**15**	**146**	**594**	1010	*305*	*14*	2085
	CLASS 7	**0**	**0**	**2**	**44**	**309**	**458**	1125	*74*	2012
	CLASS 8	**0**	**0**	**0**	**0**	**0**	**5**	**33**	46	84
	Class Total	241	3913	4743	4787	3842	2218	1838	154	21736
	Class Changes	194	1869	1955	2498	1619	1208	713	108	10164

(improved or worsened) are significantly selected by fires occurring, respectively, during and after the transition period (1990–2000).

The numbers of fires analysed for the periods 1995–1998 and 2005–2008 are, respectively, 2994 and 3970. All fires off the CD-ESAI classified cells were excluded from the analysis.

III Results

1 Fire selectivity versus LD sensitivity

The results of the analysis on fire selectivity in Sardinia for the 1995–1998 and 2005–2008 four-year periods are shown in Table 3. According to Monte-Carlo simulations, fire incidence in terms of number of events is selective for all

Table 5. 1995–1998 fires versus CD-ESAI map and 2005–2008 fires versus CD-ESAI map. Italic: values lower than expected from a random null model, $p < 0.001$; bold: values higher than expected from a random null model, $p < 0.001$.

	CD-ESAI classes	1995–1998 Number of fires	2005–2008 Number of fires
Inter-group (*a* and *b*)	*ab*W	**502**	**719**
	*ab*I	*283*	*383*
Intra-group (*a*)	*aa*W	*660*	*701*
	*aa*I	*409*	*429*
Intra-group (*b*)	*bb*W	**636**	**996**
	*bb*I	**504**	**742**
	Total	2994	3970

ESAI classes with a high significance level ($p < 0.001$). The results are the same for both considered periods: the number of fires is higher than expected by a random null model in the most 'fragile' (5) and in all 'critical' (6, 7, 8) sensitivity classes; by contrast, the number of fires is lower than expected in the lower ESAI classes, ie, the 'not affected' one (1), the 'potentially affected' (2) and the least 'fragile' (3, 4).

The obtained results hence highlighted, for both reference periods, a clear distinction between two opposite fire-proneness groups: the first (*a*) with the ESAI classes 1–4 characterized by low fire incidence; and the second (*b*) with the ESAI classes 5–8 characterized by high fire incidence (see Table 3). This finding was used as baseline for the analysis of fire behaviour in relationship with the LD dynamics in the study area.

2 Fire selectivity versus changes in LD sensitivity

During the investigated period, 4101 cells improved, 11,572 remained stable and 6063 worsened, in terms of LD sensitivity; this means that about 28% of the entire study area worsened its quality status, turning into more vulnerable ESAI classes. Analysing each ESAI 1990 class, Table 4 highlights that the 'not affected' (1) and 'potentially affected' (2) classes are those that worsened most (respectively, 80% and 47%) with respect to the total cells of the corresponding classes. The least (3) and medium (4) fragile classes got worse for about 31% and 24%, respectively; finally, the cells of the most fragile (5) and least critical (6) classes that worsened their LD status were about 23% and 21% of the total.

The results of the fire selectivity analysis on the CD-ESAI map are shown in Table 5. The number of events showed an high significant selectivity towards all the CD-ESAI classes derived ($p < 0.001$) for both time periods examined.

Regarding the intra-group changes, all cells maintained their 'fire selectivity signature' both for 1995–98 and 2005–08 fires. Even if the land quality status tended to worsen within group *a*, it did not show a direct correlation with the fire occurrence. To the contrary, within group *b*, even if the land quality status tended to improve, high fire incidence continued to characterize that area. Both fires of 1995–98 and of 2005–08 were more likely on the cells that worsened in 1990–2000, and less on those that improved; this means, on one hand, that cells that passed from a medium fragile to a more fragile and critical LD status have experienced an extremely high incidence of fires during the transition period (fires of 1995–98). Additionally, the same cells were more likely to burn in the next four-year period (2005–2008), thus suffering a repeated burning over time.

The results highlighted the existence of a mutual relationship between the LD sensitivity trend and the fire occurrence pattern in the study area only where there is a prolonged critical LD status or a passage from low-medium fragile to highly fragile-critical LD status.

IV Discussion

The high incidence of fires in the Mediterranean region constitutes a considerable threat to people and the natural environment; consequently, a good knowledge of the influence of landscape status in shaping wildfire regimes is a fundamental piece of information for understanding fire incidence patterns in human landscapes (Bajocco et al., 2010; Stolle et al., 2003).

Many studies have been carried out on the relationship between the land use/land cover of a territory and its fire regime (Bajocco and Ricotta, 2008; Cumming, 2001; Moreira et al., 2001; Nunes et al., 2005), thus focusing more on the landscape structure, rather than on its function. For instance, to the best of our knowledge, no studies analysed the fire behaviour in relationship with the LD processes of a study area.

The first analysis aimed to identify, at the regional scale, which ESAI classes were statistically preferred (or avoided) by fire in two time reference periods: 1995–98 and 2005–08. The results of both analyses clearly separate two distinct situations of fire-proneness ('negative' fire selection for 1–4 ESAI classes, and 'positive' for 5–8 ESAI classes), that reflect how the spatial distribution of different LD levels determines different fire incidence patterns. These results plainly follow the actual distribution of the land use/land cover types underlying the ESAI classes examined (data not shown here). In fact, the most natural and semi-natural Corine Land Cover (CLC) classes (belonging to the category 3 of CLC) occurred in the ESAI classes from 1 to 4, characterized by few fires, while the ESAI cells going from class 5 to 8, and positively selected by fire, fall in anthropized CLC classes including peri-urban and agricultural areas (see Bajocco and Ricotta, 2008). These findings reflect the spatial pattern of LD sensitive areas in the Mediterranean region, where land use management represents a major determinant for LD (Basso et al. 2000). In particular, urban areas, agricultural areas and the wildland-urban interface are sensitive zones (Mairota et al., 1998) due to the unsustainable management of the anthropized land uses and the progressive degradation of the neighbouring wildlands (ie, urban sprawl, industries, mines, resources overexploitation, land abandonment, deforestation, fires, etc).

Of particular interest is the drastic change of fire behaviour between ESAI classes 4 and 5. This change from the intermediate to the most fragile ESAI class marks the LD threshold that triggers a fire frequency that seems to exceed landscape sustainability. Notably, fire occurrence increased greatly from 1995–1998 to 2005–2008 (6900 and 8793 fires, respectively), and the major contribution to this rise was recorded in the most degraded ESAI classes from 5 to 8 (3725 and 5444 fires, respectively).

The second analysis of this study used a dynamic approach, with the aim of detecting the LD changes occurred in the two ESAI reference periods (1990–2000), and to link them with the number of wildfires occurred during (1995–98) and after (2005–08) the examined decade. The change detection analysis highlighted an increase in the amount of vulnerable areas: about the 28% of the investigated area worsened in LD quality status, and 23% of this amount changed to 'critical' ESAI classes.

The selectivity analysis of the 1995–98 wildfires, occurring during the transition decade (1990–2000), in relationship to the CD-ESAI classes allowed identification of potential relationships between frequent burning and increasing LD sensitivity. Unexpectedly, not all the worsening CD-ESAI classes were positively selected by past fires (1995–98), but they occurred preferentially only in cells where LD sensitivity remained high through time (even if improving) or evolved into higher levels of fragility or criticality. For instance, the cells of the CD-ESAI class *ab*W, although in ESAI 1990 belonging to the lower vulnerability classes (less fire-prone), during the transition decade suffered frequent burning, and in ESAI 2000 turned into the most fragile and critical classes (more fire-prone). This means that there was a significant fire concentration in those cells that over time highly worsened in their LD vulnerability status, and that the most critical worsening in LD vulnerability status took place typically where frequent burning occurred.

For the same relationships, the selectivity analysis of the 2005–08 wildfires, occurring after the transition decade (1990–2000), not all the worsening CD-ESAI classes were positively associated with recent fires (2005–08), but the fires occurred preferentially in cells where LD sensitivity remained high through time or evolved into high levels of fragility or criticality. This means that subsequent fires tended to happen in those areas where previous fire (1995–98) had occurred and the LD status had worsened. The results of these analyses demonstrated the existence of a fire-LD feedback dynamic that starts preferentially in areas already characterized by an initial high fragility, where many fires occur, worsening the land quality status and promoting new burning.

The results do not demonstrate the existence of a general correlation between the fire incidence and the LD status across the study area, but only in those pixels that continued to be characterized by a highly sensitive LD status through time. So, if a sort of spiral exists, it occurs only in highly fragile pixels. In this perspective, the results demonstrated the existence of what we term 'mutual early-warning processes' – rather than of spiral processes – according to which a higher fire frequency in a certain landscape should be seen as an alert that the territory is becoming more critically vulnerable over time or it is not going to significantly improve its LD status; in turn, a critically worsening tendency in a given landscape should be seen as a 'warning' signal that there is a growing risk of frequent burning in that territory. Such conclusions have strong practical implications in a perspective of 'early-warning' strategies. In landscapes where the human activity plays a key role, both driving LD evolution and influencing fire ignition, knowing the relationship between fire and LD can allow development of provisional models of land sensitivity and disturbance occurrence patterns related to changing land uses, population density dynamics and land management practices.

V Conclusions

The inter-relationship between climate, fire and LD at the local and regional level is currently not receiving appropriate attention. Future LD mitigation programs should incorporate monitoring of fire patterns at all levels to establish changes in fire type, behaviour and regimes in response to changes in influential climatic parameters (due to global warming) and in land cover structure. Fire monitoring should be linked to LD studies and the analysis of their potential feedbacks established as a basic component of 'early warning' systems for land quality dynamics. From a planning point of view, a provisional model of fire behaviour under changing vulnerability scenarios can be derived, and LD trends linked to the fire regime intensity of an area can be projected. Knowing how landscape changes and the effects of its change on the landscape quality can help policy-makers in developing strategies for fire risk assessment and decision processes in land management. Finally, the ESAI framework has been demonstrated to be a good baseline to study the dynamics of disturbances like fires with respect to land vulnerability.

Acknowledgements

We are grateful to L. Perini, M. Zitti and T. Ceccarelli (CRA-CMA, Rome) for support during the entire research project. S. Bajocco was supported by a postdoctorate fellowship from the 'AgroScenari' research project financed by the Italian Ministry of Agriculture and Forestry. We acknowledge the 'Corpo Forestale e di Vigilanza Ambientale' of Sardinia for their assistance and willingness to share their field data and scientific advice.

References

Bajocco S and Ricotta C (2008) Evidence of selective burning in Sardinia (Italy): Which land-cover classes do wildfires prefer? *Landscape Ecology* 23: 241–248.

Bajocco S, Pezzatti GB, Mazzoleni S, and Ricotta C (2010) Wildfire seasonality and land use: When do wildfires prefer to burn? *Environmental Monitoring and Assessment* 164(1–4): 445–452.

Basso F, Bove E, Dumontet S, Ferrara A, Pisante M, Quaranta G, et al. (2000) Evaluating environmental sensitivity at the basin scale through the use of geographic information systems and remotely sensed data: An example covering the Agri basin – southern Italy. *Catena* 40: 19–35.

Beverly JL and Martell DL (2005) Characterizing extreme fire and weather events in the Boreal Shield ecozone of Ontario. *Agricultural and Forest Meteorology* 133: 5–16.

Brandt J, Geeson N and Imeson A (2003) A desertification indicator system for Mediterranean Europe. Available at: http://www.kcl.ac.uk/projects/desertlinks/accessdis4me.htm

Cumming SG (2001) Forest type and wildfire in the Alberta boreal mixedwood: What do fires burn? *Ecological Applications* 11: 97–110.

D'Angelo M, Enne G, Madrau S, Percich L, Previtali F, Pulina G, et al. (2000) Mitigating land degradation in Mediterranean agro-silvo-pastoral systems: A GIS-based approach. *Catena* 40: 37–49.

Dube OP (2007) Fire weather and land degradation. In Sivakumar MVK and Ndiangúi N (eds) *Climate and Land Degradation*. Berlin: Springer, 106–132.

Enne G, Pulina G, d'Angelo M, Previtali F, Madrau S, Caredda S, et al. (2002) Agropastoral activities and land degradation: The case study of Sardinia. In: Thornes, J., Brandt, J. and Geeson, N. (eds), *Mediterranean Desertification – A Mosaic of Processes and Responses*. Chichester: Wiley, 71–82.

Finney MA (2005) The challenge of quantitative risk analysis for wildland fire. *Forest Ecology and Management* 211: 97–108.

Fiori M, Motroni A, Duce P, and Spano D (2004) A daily water balance estimate for climate risk evaluation at a local scale. In: *Acta Horticulturae*, vol. 664. ISHS. IV International Symposium on Irrigation of Horticultural Crops.

Fiorucci P, Gaetani F, Lanorte A, and Lasaponara R (2007) Dynamic fire danger mapping from satellite imagery and meteorological forecast data. *Earth Interactions* 11: 1–17.

Frost PGH and Robertson F (1987) The ecological effects of fire on savannas. In: Walker BH (ed.) *Determinants of Tropical Savannas*. Miami: ICSU Press, 93–140.

Geist HJ and Lambin EF (2004) Dynamic causal patterns of desertification. *Bioscience* 54: 817–829.

Gimeno-García E, Andreu V, and Rubio JL (2000) Changes in organic matter, nitrogen, phosphorus and cations in soil as a result of fire and water erosion in a Mediterranean landscape. *European Journal of Soil Science* 51: 201–210.

Giordano F and Marini A (2008) A landscape approach for detecting and assessing changes in an area prone to desertification in Sardinia (Italy). *International Journal of Navigation and Observation*, Article ID 549630.

Goldammer JG and de Ronde C (2004) *Wildland Fire Management Handbook for Sub-Sahara Africa*. Cape Town: Global Fire Monitoring Center, Freiburg, and Oneworldbooks.

Gonzalez-Perez JA, Gonzalez-Vila FJ, Almendros G, and Knicker H (2004) The effect of fire on soil organic matter – a review. *Environmental International* 30: 855–870.

Keeley JE and Rundel PH (2005) Fire and the Miocene expansion of C4 grasslands. *Ecology Letters* 8: 683–690.

Kosmas C, Danalatos NG, and Gerontidis S (2000a) The effect of land parameters on vegetation performance and degree of erosion under Mediterranean conditions. *Catena* 40: 3–17.

Kosmas C, Gerontidis S, and Marathianou M (2000b) The effect of land use change on soil and vegetation over various lithological formations on Lesvos. *Catena* 40: 51–68.

Kosmas C, Kirkby M, and Geeson N (eds) (1999) *Manual on Key Indicators of Desertification and Mapping Environmental Sensitive Areas to Desertification*. Brussels: European Commission, Directorate General, Project ENV4 CT 95 0119.

Kyereh B, Ninnoni R, and Agyeman VK (2006) Degraded forests are more susceptible to forest fires: Some possible ecological explanations. *Journal of Science and Technology* 26: 41–47.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, et al. (2001) The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change* 11(4): 261–269.

Larchevêque M, Montès N, Baldy V, and Dupouyet S (2005) Vegetation dynamics after compost amendment in a Mediterranean post-fire ecosystem. *Agriculture, Ecosystems and Environment* 110: 241–248.

Lavado Contador JF, Schnabel S, Gómez Gutiérrez A, and Pulido Fernández M (2009) Mapping sensitivity to land degradation in Extremadura, SW Spain. *Land Degradation and Development* 20: 129–144.

Lloret F, Calvo E, Pons X, and Dìaz-Delgado R (2002) Wildfires and landscape patterns in the Eastern Iberian Peninsula. *Landscape Ecology* 17: 745–759.

Mairota P, Thornes JB, and Geeson N (1998) *Atlas of Mediterranean Environments in Europe. The Desertification Context*. Chichester: Wiley.

Millennium Ecosystem Assessment (MEA) (2005a) *Ecosystems and Human Well-being: Synthesis*. World Resources Institute. Washington, DC: Island Press.

Millennium Ecosystem Assessment (MEA) (2005b) *Ecosystems and Human Well-being: Desertification Synthesis*. Washington, DC: World Resources Institute.

Montanarella L (2007) Trends in land degradation in Europe. In: Sivakumar MVK and Ndiangúi N (eds) *Climate and Land Degradation*. Berlin: Springer, 83–104.

Moreira F, Rego FC, and Ferreira PG (2001) Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: Implications for fire occurrence. *Landscape Ecology* 16: 557–567.

Motroni A, Canu S, Bianco G, and Loj G (2009) Monitoring sensitive areas to desertification in Sardinia: The contribute of the Regional Agrometeorological Service. In: Marini A and Talbi M (eds) *Desertification and Risk Analysis Using High and Medium Resolution Satellite Data*. Dordrecht: Springer, 117–125.

Nunes MCS, Vasconcelos MJ, Pereira, JMC, Dasgupta N, Alldredge RJ, and Rego FC (2005) Land cover type and fire in Portugal: Do fires burn land cover selectively? *Landscape Ecology* 20: 661–673.

Otto R, Krusi BO, and Kienast F (2007) Degradation of an arid coastal landscape in relation to land use changes in southern Tenerife (Canary Islands). *Journal of Arid Environment* 70: 527–539.

Pellizzaro G, Cesaraccio C, Duce P, Ventura A, and Zara P (2005) Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. *International Journal of Wildland Fire* 16: 633–641.

Pérez-Cabello F, Ibarra P, Echeverría MT, and de la Riva J (2010) Post-fire land degradation of *Pinus sylvestris* L. woodlands after 14 years. *Land Degradation and Development* 21: 145–160.

Pyne SJ, Andrews PL, and Laven RD (1996) *Introduction to Wildland Fire*. New York: Wiley.

Reynolds JF and Stafford Smith DM (2002) Do humans cause deserts? In: Reynolds JF and Stafford Smith DM (eds) *Global Desertification: Do Humans Cause Deserts?* Berlin: Dahlem University Press, 1–21.

Roberts DW (1996) Landscape vegetation modelling with vital attributes and fuzzy systems theory. *Ecological Modelling* 90: 175–184.

Salvati L and Zitti M (2007) Territorial disparities, natural resource distribution, and land degradation: A case study in southern Europe. *Geojournal* 70: 185–194.

Salvati L and Zitti M (2009) Assessing the impact of ecological and economic factors on land degradation vulnerability through multiway analysis. *Ecological Indicators* 9: 357–363.

Salvati L, Macculi F, Toscano S, and Zitti M (2007) Comparing indicators of intensive agriculture from different statistical sources. *Biota* 8: 51–60.

Salvati L, Petitta M, Ceccarelli T, Perini L, Di Battista F, and Venezian-Scarascia ME (2008) Italy's renewable water resources as estimated on the basis of the monthly water balance. *Irrigation and Drainage* 57: 507–515.

Santini M, Caccamo G, Laurenti A, Noce S, and Valentini R (2010) A multi-component GIS framework for desertification risk assessment by an integrated index. *Applied Geography* 30(3): 394–415.

Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, et al. (2007) Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management* 238: 347–364.

Stolle F, Chomitz KM, Lambin EF, and Tomich TP (2003) Land use and vegetation fires in Jambi Province, Sumatra, Indonesia. *Forest Ecology and Management* 179: 277–292.

Vasconcelos MJP, Silva S, Tomé M, Alvim M, and Pereira JMC (2001) Spatial prediction of fire ignition probabilities: Comparing logistic regression and neural networks. *Photogrammetric Engineering and Remote Sensing* 67(1): 73–81.

Vasilakos C, Kalabokidis K, Hatzopoulos J, Kallos G, and Matsinos Y (2007) Integrating new methods and tools in fire danger rating. *International Journal of Wildland Fire* 16(3): 306–316.

Van Wilgen B, Andreae MO, Goldammer JG, and Lindesay JA (1997) *Fire in Southern African Savannas: Ecology and Atmospheric Perspective*. Johannesburg: Witwatersrand University Press.