

Toward a ‘Sustainable’ land degradation? Vulnerability degree and component balance in a rapidly changing environment

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Abstract Land degradation is a process negatively affecting environmental sustainability and requires permanent monitoring for understanding its nonlinear trajectories of change over time and space. Environmental sustainability is linked to a theoretical definition of dynamic balance among various components contributing to the ecosystem quality and functioning. The aim of this study is to develop a diachronic analysis (1960–2010) of the equilibrium/disequilibrium condition of key environmental factors (climate, soil, vegetation, land-use) influencing the vulnerability of land to degradation in a Mediterranean country experiencing processes of desertification at the local scale. Three indicators of components’ balance have been proposed and tested for spatial and temporal coherence. Land classified at high vulnerability and low component’s balance has been identified as a possible target for mitigation strategies against desertification; the surface area of this class increased rapidly during 1960–2010 and concentrated in high-intensity agricultural lowlands of northern Italy.

Keywords Mediterranean region · Environmental indicators · Desertification · Sustainable development · Italy

1 Introduction

Sustainability is the potential for long-term maintenance of human well-being, which has socioeconomic, political, and cultural dimensions, and of diversity and productivity of the biological systems (Daly 1990). Sustainability therefore requires the integration of three dimensions, namely environmental quality, social equity, and economic demands to reach a developmental regime which meets the needs of the present generation without

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compromising the ability of future generations to meet their own needs (Ekins 2002; McMichael et al. 2003; Böhringer and Jochem 2007). Sustainable development aims at achieving a balance between the competing economic and social interests of human societies, alongside a balance with earth's natural environment (Arrow et al. 1995; Steer 1998; Hamdouch and Zuideau 2010).

Sustainable development thus recognizes that while economic growth has become important to modern human thinking, human development entails much more than mere economic matters (Galeotti 2007). As a matter of fact, while firms, regions, or countries can achieve varying stages of financial sustainability and human societies can achieve differing levels of social sustainability (Malkina-Pykh and Pykh 2008), various grades of environmental sustainability can be achieved when humans closely monitor and contain their impacts on earth's natural environment (Siche et al. 2008). Sustainability level measurements had been attempted through computation of key variables into thematic indicators and composite indexes (Sands and Podmore 2000) taking into consideration several aspects from the environmental, social, and economic standpoints (see Böhringer and Jochem 2007 for a review). A balanced condition among the social, economic, and environmental components of a territorial system has been regarded as a contribution to sustainability (Nourry 2008). The departure from a balanced condition among the three components of sustainability, determined using quantitative or qualitative approaches, has been incorporated as a variable in the assessment of sustainable development (Casadio-Tarabusi and Palazzi 2004).

From the environmental perspective, sustainability is reached when the rates of renewable resource harvest, pollution creation, and non-renewable resource depletion can be continued indefinitely (Daly 1990). This implies the maintenance of the factors and practices that contribute to the quality of the environment on a long-term basis (McMichael et al. 2003). Effects of unsustainable conditions are interactive, complex, and unpredictable over both time and space (Ibanez et al. 2008). Environmental sustainability is in turn linked to the dynamic balance among various aspects contributing positively or negatively to the quality of landscapes and functioning of the ecosystems (Boyce 1994; Zuideau 2006, 2007). By introducing in the measurement of sustainability those features that allow for a stable and balanced condition over time (e.g., Goodland 1995), the level of environmental sustainability may decrease as the distance from such an equilibrium condition locus increases (Casadio-Tarabusi and Palazzi 2004).

Land degradation (LD) and desertification are environmental problems impacting on agricultural and natural ecosystems in drylands and may contribute to determine relevant departures from sustainability (Montanarella 2007). Consequences in terms of biodiversity erosion, loss in ecosystem services, reduced land profitability, and soil deterioration are documented processes for desertification (Gisladdottir and Stocking 2005; Simeonakis et al. 2007; Salvati and Zitti 2008). In the Mediterranean region, the vulnerability of land to degradation has been associated with specific ecological conditions (e.g., climate aridity, soil deterioration, scarce vegetation cover) together with droughts, growing human pressure, and unsustainable land-use management (Kosmas et al. 2000a; Moonen et al. 2002; Feoli et al. 2003).

Land degradation (LD) is recognized as a process contributing to environmental (un)sustainability that needs permanent monitoring to understand its nonlinear trajectories of change over time and space (Thornes 2004). Unfortunately, analyses identifying vulnerable areas over large regions and investigating their spatial evolution over time are relatively scarce in Mediterranean Europe despite the mass of studies realized in the framework of research projects financed by European Union (Kosmas et al. 1999, 2000a,

2000b; Basso et al. 2000; Brandt 2005). Particularly, the spatial distribution of vulnerable land to degradation is a dynamic attribute of the landscape that can be affected by conditions of equilibrium or disequilibrium in the contributing factors (Ibanez et al. 2008). A correlation analysis has never been developed, to our knowledge, between the level of land vulnerability and the balance among the different components influencing it.

Based on these considerations, the present paper verifies empirically the hypothesis that the level of environmental sustainability reaches the maximum value along a certain equilibrium locus in the components' space and becomes smaller as the distance from such a locus increases (see also Thornes 2004 for a discussion on the equilibrium/disequilibrium conditions possibly leading to LD). Using LD as a multi-dimensional process linked to environmental sustainability (a lower level of land vulnerability to degradation is taken as a condition for environmental sustainability: Salvati and Zitti 2009), the present study introduces an exploratory approach (1) defining and assessing the equilibrium condition among different factors determining land vulnerability and (2) testing at the local scale if higher levels of land vulnerability are associated with larger departures from the defined condition. Departures from the equilibrium condition can be seen as a target for policy interventions in areas prone to desertification (Gisladottir and Stocking 2005; Herrmann and Hutchinson 2005; Sivakumar 2007). The approach identifies also the biophysical factors contributing the most to the departure from the equilibrium condition.

The proposed approach was developed using Italy as the case study. Italy is an interesting case for studying the relationship between land vulnerability and the balance of its environmental components (Salvati and Zitti 2009). This Mediterranean country has been designed as a hotspot for land sensitivity to degradation and desertification risk by the United Nation Convention to Combat Drought and Desertification (UNCCD) Annex IV (Salvati and Zitti 2008). Moreover, the surface of land classified as vulnerable to degradation increased rapidly from 1960 to 2010 in Italy due to the concomitant effect of climate change and growing population pressure (Salvati and Bajocco 2011).

2 Methods

2.1 Study area

The investigated area covers the whole Italy's surface extending for 301,330 km² and is composed of nearly 23 % lowlands, 42 % uplands, and 35 % mountains. The geographical partition into three regions (North, Centre, and South) is reflected in consolidated socio-demographic and economic disparities. Northern Italy is one of the most developed regions in Europe, while southern Italy is a disadvantaged region with an economic structure centered on low-income agriculture and tertiary activities including constructions, commerce, and the public sector (Salvati and Bajocco 2011).

2.2 Defining and assessing land vulnerability to degradation: a logical framework

The present study follows the official definition of 'desertification' provided by UNCCD as a 'LD in arid, semiarid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. The concept of 'land vulnerability to degradation' has been developed according to the definition provided in the MEDALUS European project (Kosmas et al. 1999). This definition, which was originated from the debate on the increasing desertification risk observed in the Mediterranean region in the last 20 years

(e.g., Basso et al. 2000; Salvati and Zitti 2008), indicates vulnerability as a state of a local system depending on quality of the natural capital, climate, and anthropogenic pressures (Kosmas et al. 2000a, 2000b).

Following this definition, the degree of land vulnerability to degradation has been assessed according to the Environmental Sensitive Area (ESA) approach developed in the framework of MEDALUS project (Kosmas et al. 1999). The approach provides a (diachronic) assessment of changes in four quality dimensions (climate, soil, vegetation, and use of land: hereafter called 'components') considered as important factors related to LD processes in the Mediterranean basin (e.g., Montanarella 2007; Sivakumar 2007; Simeonakis et al. 2007). The ESA procedure uses fourteen indicators, simplified statistical tools and spatial analysis to calculate a composite index of land vulnerability called the Environmental Sensitive Area Index (ESAI). While possible drawbacks of this framework have been widely discussed in Basso et al. (2000), Salvati and Zitti (2009), and Salvati and Bajocco (2011), the ESA approach is one of the most used procedures to evaluate the sensitivity of land to desertification. The main advantages of the ESA are the flexibility in the use of the input variables and the simplicity of the land classification based on its level of sensitivity (Ferrara et al. 2012). The outcomes of the ESA model have been extensively validated on the ground at several sites in southern Europe (Kosmas et al. 1999; Basso et al. 2000; Salvati and Zitti 2008), and a regional assessment (Lavado Contador et al. 2009) indicates the ESAI as a proxy for LD processes and identifies significant correlations with a number of indicators of soil degradation. Finally, Ferrara et al. (2012) evaluated the stability of the ESAI using statistical analysis and the sensitivity to changes in the composing indicators. Results indicate that the ESAI is a stable and reliable index scarcely affected by spatial and temporal heterogeneity in the composing indicators.

Notably, LD is a complex phenomenon driven by multiple factors; some of them could be underestimated or neglected in the ESA scheme (Montanarella 2007). In previous works, however, it was demonstrated that, by analyzing a larger number of candidate indicators of desertification (more than 50 variables linked to six distinct LD processes), the distribution of vulnerable land to degradation in Italy at an enough detailed spatial scale is comparable to that obtained using the ESAI (Salvati et al. 2011). Using multivariate statistical tools, correlations among candidate indicators have been also analyzed and provided similar results to those obtained from the application of the ESA scheme (e.g., Salvati and Zitti 2009).

2.3 Data and variables

According to the ESA framework, fourteen variables (3 describing climate quality, 4 for soil quality, 4 for vegetation quality, and 3 for land-use/land management) were considered in the present study: the average annual rainfall rate, aridity index (the long-term ratio of annual precipitation to annual reference evapotranspiration), and aspect as proxies for climate quality; soil depth and texture, slope, and parent material as proxies for soil quality; the degree of vegetation cover, fire risk, protection offered by vegetation against soil erosion, and the degree of resistance to drought shown by natural vegetation as proxies for vegetation quality; population density, annual growth rate of population and intensity in the use of land as proxies for land-use quality.

At our knowledge, the considered layers are the most reliable, updatable and referenced data currently available to be used in the regional and national assessment of the ESAI in a Mediterranean country (Salvati et al. 2011). However, comparable data, needed to develop the full ESAI model with national coverage and detailed spatial scale, were available only

at limited dates. According to data availability, the level of land sensitivity was therefore investigated at 4 years (1960, 1990, 2000, and 2010). A detailed description of the considered variables was provided in previous studies (Kosmas et al. 1999, 2000a, 2000b; Basso et al. 2000; Salvati and Zitti 2008). All variables have been derived at the lowest available spatial resolution from official data sources including meteorological statistics, population and agricultural censuses, CORINE land cover maps, and a soil quality map provided by the European Joint Research Centre.

Climate variables were calculated on a 10-year base using information collected in the Agro-meteorological Database of the Italian Ministry of Agriculture. The database relates to gauging data collected daily from various meteorological and hydrological networks (Italian Ministry of Agriculture, National Hydrological Service, Italian Air Force, and some minor networks) operating with nearly 3,000 weather stations since 1951. Meteorological data were interpolated through geo-statistical procedures (using elevation, latitude, and distance to the sea as ancillary variables) to ensure the homogeneous national coverage. Aspect was derived from elaboration on the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) global digital elevation model (DEM) at 30-m resolution scale generated from stereoscopic pairs of optical ASTER images (Salvati and Bajocco 2011).

Soil data derived from the European Soil Database at 1 km² pixel resolution produced by Joint Research Center in Ispra (JRC). Ancillary information was derived from national databases of soil characteristics (Salvati and Zitti 2008). Considering the examined time span, the variables have been regarded to be static during the study period because they change slowly, if at all or, by their nature, are infrequently measured (Salvati and Zitti 2009). Vegetation variables derived from elaboration on two comparable maps: the CORINE-like 'Topographic and Land Cover Map of Italy' produced by the National Research Council and the Italian Touring Club in 1960 and three CORINE land cover maps, respectively, dated 1990, 2000, and 2006. The maps were already used for multi-temporal analysis of land cover and other environmental indicators at the regional scale in Italy (Salvati and Bajocco 2011). Land-use quality has been quantified as the result of population dynamics and selected land-use changes. Population data derived from the National Censuses of Population carried out every 10 years by the Italian National Institute of Statistics (ISTAT 2006). Land-use intensity derived from the previously described maps.

The 14 variables described below were transformed into vulnerability indicators using the ESA score system (Basso et al. 2000; Simeonakis et al. 2007; Salvati and Zitti 2008). This system (see Salvati and Bajocco 2011 for an analytical description of the scores assigned to each variable) uses coefficients ranging from 1 (the lowest vulnerability score) to 2 (the highest vulnerability score) applied separately to each variable to derive its contribution to the level of land vulnerability to degradation and was based on the estimated degree of correlation between the mentioned variables and independent field indicators of LD measured in several pilot areas in southern Europe (Kosmas et al. 1999; Salvati and Zitti 2008; Lavado Contador et al. 2009). Ferrara et al. (2012) demonstrated the reliability of the score system and the stability of the derived indicators.

2.4 Thematic indicators and the composite index

According to the ESA scheme, four thematic indicators (Climate Quality Index: CQI, Soil Quality Index: SQI, Vegetation Quality Index: VQI, and land Management Quality Index:

MQI) describing the examined environmental components (climate, soil, vegetation, land-use/land management) have been calculated as the geometric mean of the selected variables transformed using the related coefficients. Indicators range from 1 (indicating the lowest land vulnerability to degradation) to 2 (the highest vulnerability to degradation). The ESAI was derived as the geometric mean of the four thematic indicators. The ESAI ranges from 1 (indicating the lowest land vulnerability to degradation) to 2 (the highest vulnerability to degradation).

The ESAI maps have been produced using the ArcGIS software (ESRI Inc., Redwoods, USA) after the various layers were rasterized, registered, and referenced to the elementary 1 km^2 spatial unit. The minimum spatial unit has been selected according to Basso et al. (2000). Following Salvati and Bajocco (2011), Italian land was classified into three levels of vulnerability ('non-affected or potentially affected land': $\text{ESAI} < 1.225$, 'fragile land': $1.225 < \text{ESAI} < 1.375$, and 'critical land': $\text{ESAI} > 1.375$).

2.5 Statistical analysis

By using the 'zonal statistics' tool provided with ArcGIS software (ESRI Inc., Redwoods, USA), the average value of each component indicator (CQI, SQI, VQI, and MQI) and the ESAI was estimated for 1960, 1990, 2000, and 2010 at a detailed geographical scale covering the whole national territory subdivided into 773 agricultural districts identified by ISTAT (2006) on the base of both biophysical (topography, local climate, soil) and socioeconomic variables (prevailing crop systems, characteristics of the rural landscape, settlements). The procedure computes a surface-weighted average of the ESAI values belonging to that unit (Salvati and Zitti 2008). Agricultural districts allow for the analysis of changes in land vulnerability and imbalances in the four ESAI components at a spatial scale which is informative for non-technical stakeholders, consistent with the characteristics and resolution of the variables selected, and meaningful for the identification of strategies contrasting desertification. Finally, agricultural districts represent in Italy homogeneous local systems and economically relevant spatial units possibly indicating the impact of environmental policies carried out at both regional and local levels (e.g., Salvati and Zitti 2008).

2.6 Assessing the components' balance condition

The operational definition of components' balance derives from the observation that, since environmental sustainability consists of several relevant aspects (e.g., Goodland and Daly 1996), it is impractical to assume complete substitutability among them: Hence, a concept of balance is introduced for practical purposes (Ekins 2002). Moreover, due to the criticisms to assumptions of complete substitutability and equal weighing of different components when calculating environmental quality indicators (Myers and Macnaghten 1998), it was suggested (Chakravarty 2003; Lawn 2003; Casadio-Tarabusi and Palazzi 2004; Salvati and Zitti 2009) to identify an equilibrium condition with the aim of quantifying the possible deviation from environmental conditions leading to land vulnerability.

The four thematic indicators of land vulnerability in the ESA scheme (CQI, SQI, VQI, and MQI) were thus considered for the analysis of components' balance. The equilibrium locus was determined to be the diagonal line in the space of variables; this procedure satisfies a minimal set of axioms that improves on the one proposed by Chakravarty (2003). The ESA scheme provides for an implicit standardization of

variables and indicators (in both entity and direction) that range from 1 to 2. This allows for full statistical comparability among components. Three indicators of balancing in the four ESAI components have been calculated by year and district: (1) The coefficient of variation of the components' scores calculated as percent ratio of the standard deviation of the four scores measured at each year and district to the average of the four scores, (2) The ratio of the range (max–min) observed in the four components' scores to the average ESAI value, and (3) the ratio of the maximum score observed among the four components to the average of the four scores. These indicators provide an estimation of the departure from the environmental condition where all components contribute the same to the overall level of land vulnerability. Higher values of the three indicators indicate an imbalanced condition among components. Two distinct sub-periods (1960–1990 and 1990–2010), supposed to represent distinct environmental and socioeconomic conditions in Italy (Salvati and Bajocco 2011), were further analyzed.

Pair-wise correlations between indicators of components' balance were checked using Pearson and Spearman statistics testing for significance at $p < 0.05$ after Bonferroni's correction for multiple comparisons. Based on the results of this analysis, one of the three indicators was chosen for further elaborations. The same statistical tests have been developed to assess the pair-wise relationship between the selected indicator of components' balance and eleven variables derived from the application of the ESA model (listed in Table 1). The list includes the ESAI, the four thematic indicators, and six additional variables elaborated at the same spatial scale (i.e., agricultural districts): The percentage of land classified at 'fragile' (%F) and 'critical' (%C) categories, and the coefficient of variation of the scores observed in each district for three thematic indicators (CQIv, SQIv, and VQIv) and the composite index (ESAIv) taken as proxies of spatial heterogeneity in land vulnerability. To investigate the impact of the selected variables on the indicator of components' balance a multiple linear regression was finally carried out on the eleven variables using a backward stepwise procedure with F to remove and F to enter fixed, respectively, at 11 and 10. Results include intercept and coefficient estimates as well as significance levels for the coefficient and the overall model estimate.

Table 1 Variables considered in the present study and the related measurement scale by agricultural district in Italy

Acronym	Variable name	Measurement scale
ESAI	Environmental Sensitive Area Index	Score ranging from 1 to 2
ESAIv	Coefficient of variation in the ESAI score	Percentage
CQI	Average Climate Quality Index	Score ranging from 1 to 2
CQIv	Coefficient of variation in the CQI score	Percentage
SQI	Average Soil Quality Index	Score ranging from 1 to 2
SQIv	Coefficient of variation in the SQI score	Percentage
VQI	Average Vegetation Quality Index	Score ranging from 1 to 2
VQIv	Coefficient of variation in the VQI score	Percentage
MQI	Average land Management Quality Index	Score ranging from 1 to 2
%F	Surface land classified as 'fragile' ($1.225 < \text{ESAI} < 1.375$)	Percentage
%C	Surface land classified as 'critical' ($\text{ESAI} > 1.375$)	Percentage

3 Results

3.1 The indicator of equal balance among ESAI components

The analysis of the relationship between the three indicators of equal balance in the ESAI components based on the pair-wise linear correlation matrix is shown in Table 2. All comparisons were found significant at $p < 0.0001$ with correlation coefficients always higher than 0.7 ($n = 773$ districts). The same results have been obtained using Spearman rank correlation analysis (data not shown). This indicates that the three indicators provided comparable results in terms of deviation from the equilibrium condition in the four examined components (climate, soil, vegetation, and land-use). Based on these results, the coefficient of variation calculated over the vulnerability score of the four components (labeled with (i) in Table 2 and hereafter called the EQI) was considered in further analyses. The statistical distribution of the EQI in Italy was shown in Fig. 1 for two selected years (1960 and 2010) and indicates normality in both years.

3.2 Evaluating the relationship among land vulnerability and ESAI components' balance

Trends in the EQI and ESAI in Italy have been illustrated in Table 3. The average EQI was 0.522 in 1960 and decreased to 0.518 in 2010 indicating a relatively more balanced distribution of the four ESAI components in the recent years (Mann–Whitney nonparametric U test, $p < 0.05$, $n = 773$). A reverse trend was observed in the ESAI which increased rapidly over time at the country level. At the regional scale, the EQI was found higher in northern Italy than in southern Italy at all examined years. This result is in contrast with the spatial distribution of the ESAI which showed a reverse north–south gradient (higher ESAI scores found in southern Italy).

The highest scores of the EQI were observed in 1960 in the mountain belt of Apennines and Alps (Fig. 2) and decreased with elevation. The lowest scores have been observed in the most vulnerable areas of the country (Apulia, Sardinia, and Sicily). On average, this indicates that the four components of the ESAI are more balanced in territorial contexts where the level of land vulnerability to degradation is high. The increase in the EQI during 1960–2010 was mainly concentrated in the flat areas of northern Italy and in selected districts of Latium, Apulia, and Sicily.

Interestingly, the spatial distribution of changes in the EQI was different in 1960–1990 and 1990–2010 (Fig. 3). During the former period, the EQI increased mainly in north-eastern Italy, Tuscany and along the coasts of Sicily and Sardinia, possibly indicating that a

Table 2 Pearson correlation coefficients between the three examined indexes of components' balance in the ESAI

Comparison	1960	1990	2000	2010
(i) versus (ii)	0.92	0.84	0.83	0.83
(ii) versus (iii)	0.78	0.80	0.81	0.72
(i) versus (iii)	0.88	0.89	0.90	0.86

(i) the coefficient of variation of the four components (hereafter called the EQI), (ii) the ratio of the range (max–min) component score to the average ESAI, and (iii) the ratio of the maximum component score to the average ESAI value; all correlation coefficients are significant at $p < 0.0001$

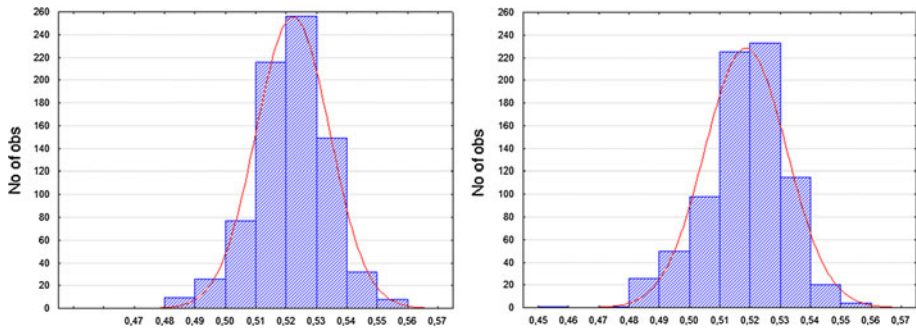


Fig. 1 Statistical distribution of the EQI (indicating the coefficient of variation of the four components of land vulnerability) in 1960 (left) and 2010 (right) in Italy by agricultural district

Table 3 Trends over time (1960–2010) in the EQI and ESAI in Italy by geographical division (*n* indicates the number of agricultural districts evaluated in the analysis)

Division	<i>n</i>	1960	1990	2000	2010	% change 1960–2010	% change 1960–1990	% change 1990–2010
<i>Average EQI</i>								
North	329	0.526	0.530	0.529	0.524	−0.005	0.026	−0.052
Centre	184	0.523	0.517	0.516	0.518	−0.018	−0.040	0.015
South	260	0.516	0.511	0.504	0.511	−0.022	−0.036	0.000
Italy	773	0.522	0.520	0.518	0.518	−0.014	−0.010	−0.019
<i>Average ESAI</i>								
North	329	1.318	1.330	1.332	1.353	0.052	0.030	0.085
Centre	184	1.329	1.346	1.348	1.350	0.032	0.041	0.017
South	260	1.372	1.384	1.400	1.384	0.019	0.031	0.000
Italy	773	1.339	1.352	1.359	1.363	0.036	0.033	0.039

single component was rapidly turning to the worse influencing the overall balance among the four components. In the latter period, the increase in the EQI was concentrated in central and southern Italy (except for Sardinia) with the reverse spatial pattern compared to the ESAI which increased mainly in northern Italy. As a matter of fact, the relationship between the percent changes in the EQI and the ESAI was linear and negative (Spearman $r_s = -0.73$ and Pearson $r = -0.71$, both $p < 0.001$, $n = 773$) in 1990–2010 (Fig. 4) being nonsignificant in 1960–1990 (Spearman $r_s = -0.04$ and Pearson $r = -0.03$, both $p > 0.05$, $n = 773$).

3.3 The contribution of the individual components to the EQI

Results of the pair-wise nonparametric correlation analysis (Table 4) carried out between the EQI and eleven selected variables elaborated in the framework of the ESA model indicate that different patterns have been observed through time in the components’ balance at the district scale. The SQI correlated positively with the EQI in 1960 ($r_s = 0.44$) and 2010 ($r_s = 0.16$), while the VQI correlated positively with the EQI in 2000 ($r_s = 0.18$) and 2010 ($r_s = 0.28$), indicating that soil and vegetation quality are the two factors

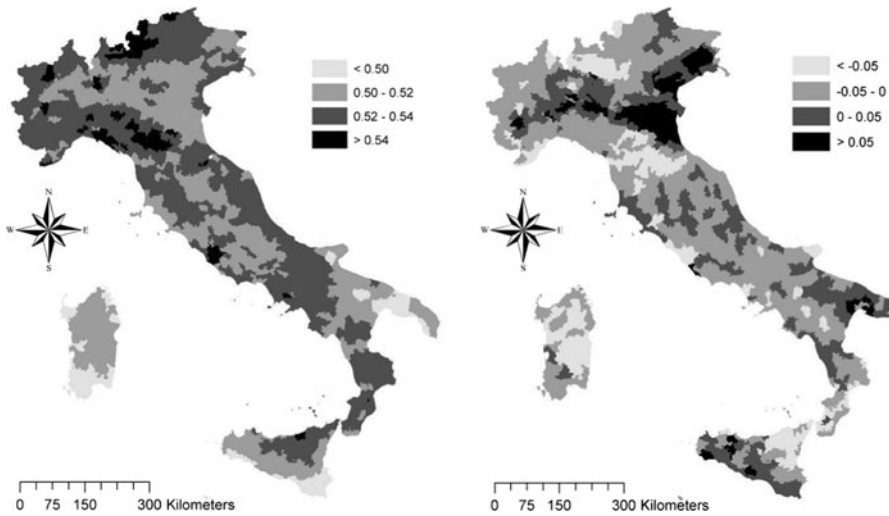


Fig. 2 Spatial trend in the EQI (left: 1960; right: annual % change observed during 1960–2010) in Italy

contributing the most to the balance among components. The spatial variability in the VQI, however, correlated negatively with the EQI in 1990, 2000, and 2010. The CQI and its spatial variability at the local scale (CQIV) were the variables showing the highest negative correlation coefficients with the EQI in all examined years ($r_s = -0.63$ in 1960 and $r_s = -0.58$ in 2010), thus indicating that high and intermediate climate quality is associated with imbalanced conditions among components. Interestingly, the correlation between the ESAI and the EQI scores was weakly significant only in 1960, 1990, and 2000, suggesting that imbalanced conditions among components can be found in both vulnerable and non-vulnerable areas to degradation. A stepwise regression analysis (Table 5) partly confirmed the results previously described: The indicators showing the highest positive impact on the EQI were the SQI, the VQI and, at a lesser pace, the MQI in both 1960 and 2010. The indicators of spatial variability in all considered components (CQI, SQI, VQI), together with the CQI in 1960 and the ESAI in 2010 contributed negatively to the EQI in both years.

3.4 Identifying particularly sensitive areas according to ESAI and EQI

The spatial distribution of Italian agricultural districts classified, on average, in the ‘critical’ land class (ESAI > 1.375) and with markedly imbalanced components (EQI > 0.53, which is one standard deviation higher than the 4-year average EQI = 0.52) was analyzed. Areas identified using these two indicators have been regarded as particularly sensitive to degradation (Salvati and Bajocco 2011). The spatial distribution of Italian districts with critical environmental conditions and imbalanced values of the ESAI is shown in Fig. 5 separately for 1960 and 2010. While in 1960, areas classified as ‘critical and imbalanced’ were relatively sparse over the Italian territory; in 2010, this class concentrated in the flat (high-intensity) agricultural areas of northeastern Italy where the level of land vulnerability to degradation has grown more in the last decade.

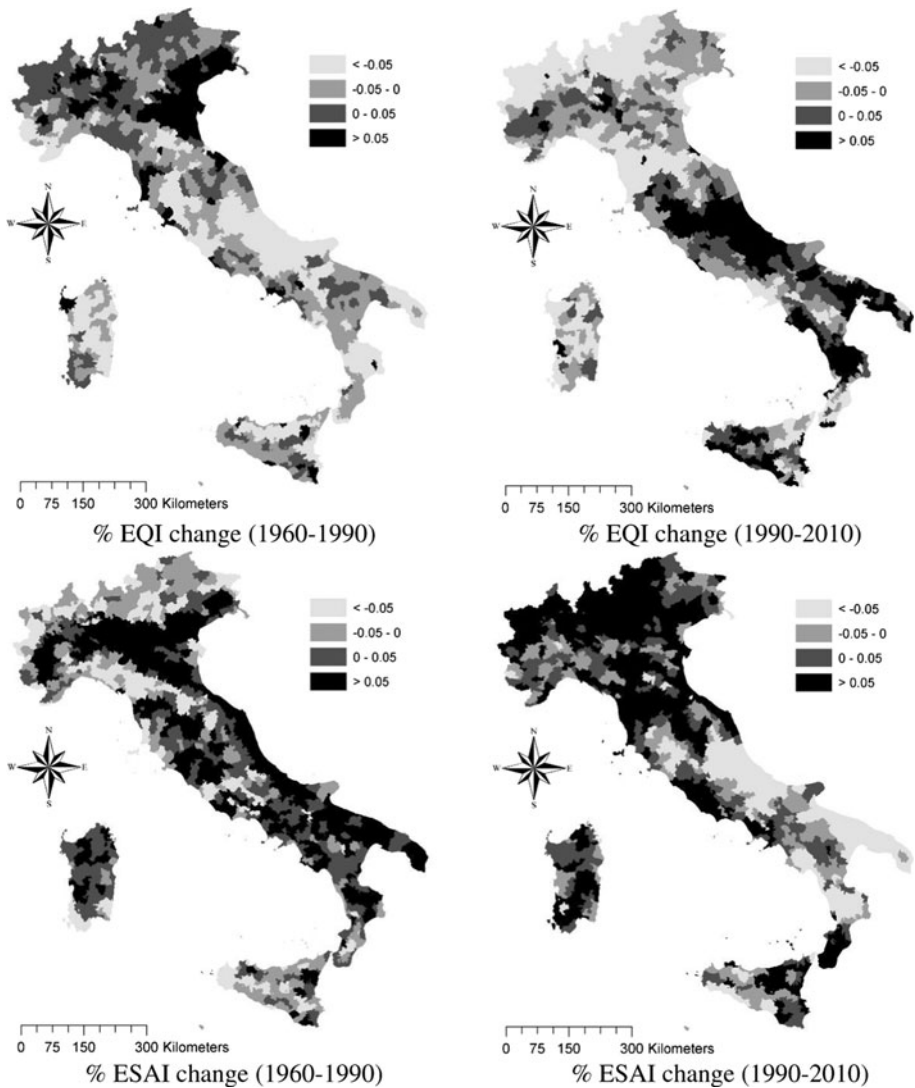


Fig. 3 Annual rate of change (%) in the EQI and ESAI in Italy by time period

4 Discussion

Based on four thematic indicators aimed at quantifying changes over time in the degree of land vulnerability to desertification (Kosmas et al. 1999; Basso et al. 2000), the present study introduced an approach which evaluates the equilibrium/disequilibrium in the components contributing to LD. Equilibrium is considered as an environmental condition that can minimize internal imbalances between the various components (Niemeijer 2002; Malkina-Pykh and Pykh 2008; Nader et al. 2008; Nourry 2008). The hypothesis, referring to the 'component balance' concept originated from development studies (Casadio-Tarabusi and Palazzi 2004) is that, to guarantee the maximum potential contribution to

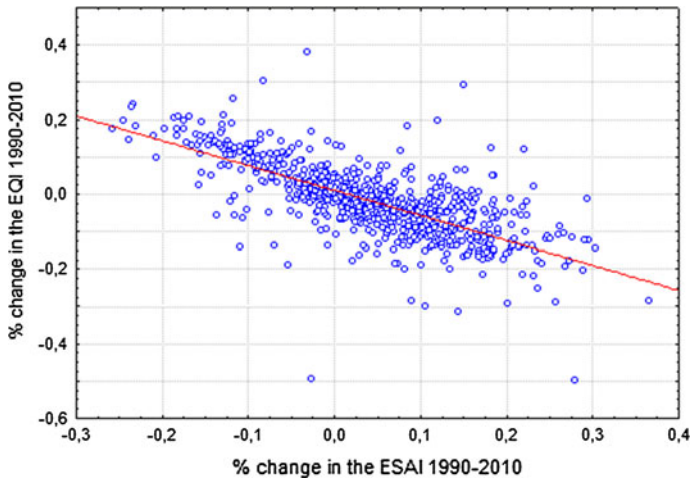


Fig. 4 The relationship between the EQI and the ESAI in the period 1990–2010 by agricultural district

Table 4 Spearman nonparametric correlation analysis between the balancing EQI index and selected ESAI variables by year (significance was tested at $p < 0.05$ after Bonferroni's correction for multiple comparisons)

Variable	1960	1990	2000	2010
ESAI	-0.21*	-0.20*	-0.23*	-0.02
ESAIv	0.09	-0.28*	-0.32*	-0.23*
CQI	-0.63*	-0.68*	-0.72*	-0.58*
CQIv	-0.35*	-0.25*	-0.21*	-0.29*
SQI	0.44*	0.14	0.06	0.16*
SQIv	0.15	-0.09	-0.11	-0.04
VQI	-0.08	0.14	0.18*	0.28*
VQIv	0.09	-0.30*	-0.35*	-0.29*
MQI	-0.09	0.11	0.11	0.12
%F	-0.17*	-0.14	-0.14	0.04
%C	-0.23*	-0.36*	-0.43*	-0.20*

sustainability, the dimensions chosen to represent the degree of environmental vulnerability in a region should be balanced. While the imbalance in various components of sustainability does not necessarily reflect negative environmental conditions, to assume that the (dynamic) balance of multiple components as the optimal condition for sustainability is an important issue when the substitution of these components is not complete (Salvati and Zitti 2008).

Three indicators were tested to evaluate the departures from the equilibrium condition over time and space using agricultural districts in Italy, a country considered as an hotspot for desertification in the Mediterranean region. Since all indicators showed strictly comparable trends, one of them (the EQI) was selected as a proxy for a balanced environmental condition and tested for correlation with independent variables. The approach is easy to implement even with a larger number of variables entering a composite index of environmental sustainability (e.g., Malkina-Pykh and Pykh 2008; Nourry 2008; Siche et al. 2008).

Table 5 Backward stepwise regression results by year with the EQI as dependent variable

	β	β standard error	b	B standard error	t^*
1960: adjusted $R^2 = 0.94$; $F_{(9,763)} = 1,392$, $p < 0.0001$ std. error of estimate: 0.003					
Intercept			0.519	0.006	83.2
ESAI	-3.240	0.113	-0.742	0.026	-28.4
CQI	0.777	0.059	0.102	0.007	13.2
CQIv	-0.287	0.008	-0.378	0.011	-32.1
SQI	1.605	0.038	0.238	0.005	42.0
SQIv	-0.045	0.009	-0.022	0.004	-4.6
VQI	1.519	0.044	0.211	0.006	33.9
VQIv	-0.101	0.010	-0.043	0.004	-9.5
MQI	1.738	0.060	0.179	0.006	28.9
%F	0.074	0.020	0.000	0.000	3.6
2010: adjusted $R^2 = 0.94$; $F_{(7,765)} = 1,806$, $p < 0.0001$; std. error of estimate: 0.003					
Intercept			0.504	0.003	140.1
ESAI	-1.845	0.019	-0.381	0.003	-95.4
CQIv	-0.267	0.008	-0.367	0.012	-30.3
SQI	0.975	0.011	0.162	0.001	81.4
SQIv	-0.075	0.009	-0.041	0.005	-7.6
VQI	1.357	0.017	0.131	0.001	77.4
VQIv	-0.110	0.011	-0.036	0.003	-9.8
MQI	0.905	0.013	0.090	0.001	65.4

* all t statistics are significant at $p < 0.0001$

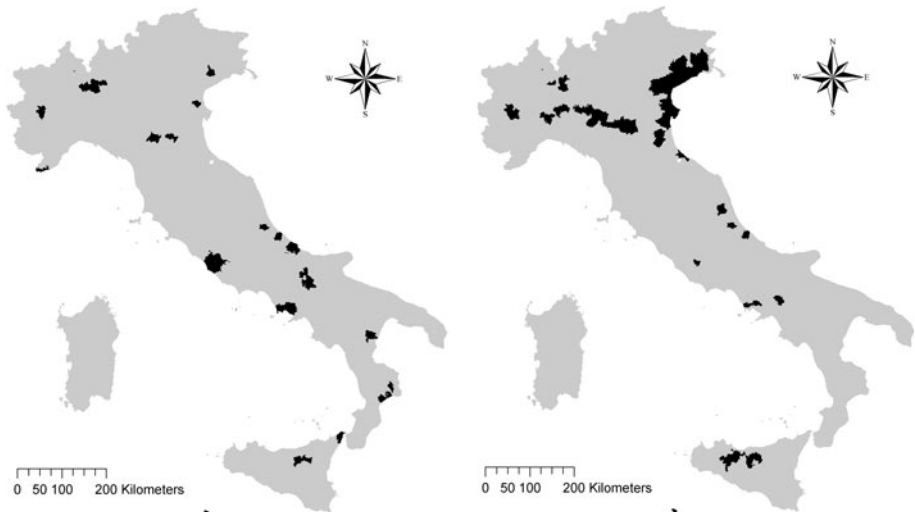


Fig. 5 Spatial distribution of the Italian agricultural districts showing 'critical' values of the ESAI and imbalanced conditions in the four ESAI components (see the methodological chapter for details)

Results indicate that the equilibrium condition is associated with territorial contexts characterized by both low and high vulnerability to LD and identify the components contributing the most to the equilibrium condition. Interestingly, soil and vegetation are the components mostly associated with equilibrium conditions at the local scale (see also Simeonakis et al. 2007): In other words, poor soil quality and scarce vegetation cover are the variables mainly associated with strongly imbalanced environmental conditions, suggesting that specific measures containing soil degradation and protecting natural vegetation (e.g., from fires, overgrazing, or edification) could be effective in the improvement of components' balance. This could be seen also as indirect measures against territorial disparities in the quality of natural resources (e.g., Hamdouch and Zuindeau 2010).

This finding opens up an original investigation field aimed at (1) classifying territorial contexts at balanced or imbalanced conditions and (2) identifying the 'converging' and 'diverging' components toward the equilibrium. The fact that climate quality resulted as the component mostly associated with imbalanced conditions confirm the importance attributed to this driver of LD by previous studies carried out at both the global or continental level (e.g., Feoli et al. 2003; Montanarella 2007; Sivakumar 2007) and the Mediterranean (e.g., Lavado Contador et al. 2009) or Italian level (e.g., Salvati and Zitti 2009).

Since climate is only indirectly influenced by environmental policies, this suggests how difficult is implementing effective policies for the mitigation of LD at the local and regional scale (Herrmann and Hutchinson 2005). As a consequence, the present study confirms the importance of considering together different components as possible targets for integrated environmental policies (Salvati and Zitti 2008). Moreover, the locus that indicates the equilibrium condition among the four components contributing to land vulnerability is a possible target for measures mitigating desertification risk (Zuindeau 2007).

As a conclusive result, this study identified the most vulnerable areas in Italy where the departure from balanced conditions in terms of LD was markedly high. This approach contributes to a permanent monitoring system that combines information on the long-term sustainability of regional systems with the simplicity and flexibility of a composite index of land vulnerability (Feoli et al. 2003). Areas characterized with high degree of land vulnerability and imbalanced environmental components are candidate targets for desertification risk mitigation measures (Gisladdottir and Stocking 2005), and the designation criterion proposed in this paper should be considered in national and regional policies such those developed in the National Action Plan to combat desertification. The proposed approach is suited to monitor land at an enough detailed spatial scale over changing environmental conditions and may enrich substantially the information provided with the ESA framework.

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