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Complex Adaptive Systems, soil degradation and land sensitivity to desertification: A multivariate assessment of Italian agro-forest landscape

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HIGHLIGHTS

- We study the relation among socio-ecologic indicators and land degradation in Italy
- We develop an exploratory framework to analyse agro-forest complex systems
- Soil and vegetation are relevant in regulating system's equilibrium in the long-term.
- System's rapidity of change is correlated with the level of land sensitivity.

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ABSTRACT

Degradation of soils and sensitivity of land to desertification are intensified in last decades in the Mediterranean region producing heterogeneous spatial patterns determined by the interplay of factors such as climate, land-use changes, and human pressure. The present study hypothesizes that rising levels of soil degradation and land sensitivity to desertification are reflected into increasingly complex (and non-linear) relationships between environmental and socioeconomic variables. To verify this hypothesis, the Complex Adaptive Systems (CAS) framework was used to explore the spatiotemporal dynamics of eleven indicators derived from a standard assessment of soil degradation and land sensitivity to desertification in Italy. Indicators were made available on a detailed spatial scale (773 agricultural districts) for various years (1960, 1990, 2000 and 2010) and analyzed through a multidimensional exploratory data analysis. Our results indicate that the number of significant pair-wise correlations observed between indicators increased with the level of soil and land degradation, although with marked differences between northern and southern Italy. 'Fast' and 'slow' factors underlying soil and land degradation, and 'rapidly-evolving' or 'locked' agricultural districts were identified according to the rapidity of change estimated for each of the indicators studied. In southern Italy, 'rapidly-evolving' districts show a high level of soil degradation and land sensitivity to desertification during the whole period of investigation. On the contrary, those districts in northern Italy are those experiencing a moderate soil degradation and land sensitivity to desertification with the highest increase in the level of sensitivity over time. The study framework contributes to the assessment of complex local systems' dynamics in affluent but divided countries. Results may inform thematic strategies for the mitigation of land and soil degradation in the framework of action plans to combat desertification.

1. Introduction

As a living system providing key ecosystem services and representing the fundamental part of the natural capital in land, soil is often managed to support multiple benefits, such as food production, biodiversity conservation, water availability, soil health and environmental quality at large (Gisladottir and Stocking, 2005). Soil and landscape degradation driven by unsustainable land management and biophysical processes are considered key factors of desertification (Herrmann and Hutchinson, 2005). Following the definition provided by United Nations Convention to Combat Desertification, soil degradation reflects a decline of the biological and/or economic productivity in semi-arid and dry areas, determining a loss in the ecological complexity of cropland, pastures, and woodland (Ferrara et al., 2012). The severity of soil and landscape degradation

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depends on the initial status of the land, on the magnitude of drivers that cause pressures on land, on the responses of the land system and on the feedback impact of these responses on land resources (Juntti and Wilson, 2005).

The main causes of soil degradation and increasing land sensitivity to desertification in the Mediterranean basin are primarily human-induced (Feoli et al., 2003) and are generally more pronounced in areas with semi-arid or dry climate conditions, with water being the main factor limiting ecosystem performance, resilience and recovery (Simeonakis et al., 2007; Lavado Contador et al., 2009; Ferrara et al., 2014). In rural areas, soil degradation occurs mainly through deforestation or unsustainable cropping, irrigation or grazing practices, which, in turn, stems from the socioeconomic conditions in which the people live, possibly altering the physical attributes of the system (Imeson, 2012). Such actions generate positive or negative impacts, leading to specific responses that may feedback driving forces, pressures and the state of the system with the corresponding impacts (MEA, 2005; Mancino et al., 2014). The European Union promoted a soil thematic strategy, which identified the following threats to soil functions: erosion, organic matter decline, loss of biodiversity, compaction, sealing, point or diffused contamination, pollution and salinization (Montanarella, 2007).

As clearly outlined in previous studies (e.g., Salvati and Zitti, 2008; Santini et al., 2010), the multifaceted ecological and socioeconomic relationships characterizing soil degradation and increasing land sensitivity to desertification in the Mediterranean region justifies the development of analytical frameworks and statistical methodologies capable to address and quantify the spatiotemporal evolution of complex systems. This will provide information useful to implement strategies for a sustainable land management, intended as a way to preserve fertile soils, to recover degraded soil and to mitigate land sensitivity to desertification (Fernandes and Burcroff, 2006). Kelly et al. (2015) have pointed out the efficiency of the Complex Adaptive Systems (CAS) paradigm when analyzing socio-ecological problems. The Drylands Development Paradigm confirms the efficiency of the CAS approach applied to socio-ecological systems in the specific case of land threatened by degradation and desertification risk.

A Complex Adaptive System (CAS) is a self-similar collective of interacting adaptive agents. CAS are special cases of complex systems, adapting to the changing environment and formed by multifaceted components (Holland, 2006). Systems are complex having non-linear relationships among their components characterized by positive and negative feedback mechanisms with inseparability and intertwined functioning. They are adaptive, in that the actors' behavior self-organizes the system on the basis of the external and internal inputs that are simultaneously determinants and products of the functioning of the system (Salvati and Zitti, 2008). What distinguishes a CAS from pure multi-agent systems is the necessity to be holistically approached in relation to – and not in isolation from – the socio-environmental systems in which they are embedded. High adaptive capacity also characterizes CASs in turn increasing resilience in the face of perturbation and interactions among the involved agents (any element in the system is affected by and affects several other elements; interactions are primarily but not exclusively with immediate neighbors and the nature of the influence is modulated by space).

Complex systems evolve and their recurrent behavior is co-responsible for their present behavior, often operating under far from equilibrium conditions (Frazier et al., 2013). Based on these characteristics, a CAS may simulate – supposedly better than other models – the interplay between several factors involved in a complex system undergoing continuous changes and feedback relations such as rural land experiencing processes of soil and landscape degradation caused by multiple interacting external and internal stimuli (McMichael et al., 2003).

In the present study, soil degradation and land desertification processes are interpreted within the framework of Complex Adaptive Systems and a specific procedure was developed to assess the changing level of soil degradation and land sensitivity to desertification in Italy over the last fifty years (1960–2010), especially focusing on agro-forest landscapes. A comprehensive assessment of a soil-landscape CAS based on a set of biophysical and socioeconomic indicators analyzed through non-linear and non-parametric statistics is the objective of this paper. The proposed framework verifies if the relations between CAS elements increase in intensity and complexity during the study period and if such changes are correlated with the (growing) level of soil degradation and land sensitivity to desertification in Italy (Abson et al., 2012).

This framework is a specific development of the approach to complexity in soil-landscape interactions as proposed by Thornes (2004). This allows evaluating changes over time in four issues: (i) non-linear relationships among system's variables; rapidity of change of (ii) system's variables, and (iii) elementary spatial units; and (iv) the relationship between rapidity of changes in each spatial unit and the initial state of each system's variable. Despite using a finite number of indicators in the system's description, the exploratory data analysis proposed here may evaluate comparatively the transitions at the base of the development path of homogeneous rural districts towards land degradation in relation with selected structural characteristics of each district. Outcomes of the proposed assessment may inform innovative approaches to sustainable land management (Salvati and Zitti, 2009), contributing to define specific strategies for the mitigation of soil and landscape degradation in the framework of national and regional intervention plans – e.g., National Action Plans – to combat desertification (Briassoulis, 2004). Multi-targeted and multi-scalar monitoring is especially needed in dynamic local contexts (such as the Mediterranean region) to ascertain the latent relationship among biophysical and anthropogenic factors (Ibanez et al., 2008).

2. Methods

2.1. Study area

The investigated area covers the whole Italy (301,330 km^2). The national territory was divided into three geographical divisions (North, Centre, South) with similar areal coverage but different socio-ecological characteristics. The country area (23% flat, 42% hilly and 35% mountainous) is characterized by a temperate-dry Mediterranean climate. Elevation classes and geographical divisions were defined by ISTAT (1958) for the whole national territory. The three geographical divisions of Italy reflect a supra-regional spatial level merging a number of administrative regions ranging from 4 (central Italy) to 8 (northern and southern Italy). Country land was classified into three elevation belts (lowland: <100 m; 100 m < upland < 600 m; mountains > 600 m) according to the average elevation of each municipality. Generally, rainfalls increase with elevation and latitude and the reverse pattern was found for temperature. Soils and landscapes share a high functional diversity shaped by the millenary interplay between nature and humans. Similar to other countries in southern Europe, Italy shows important disparities in economic and social development and environmental resource availability at both the regional and local scale (Salvati and Bajocco, 2011).

2.2. Assessing land sensitivity to degradation: a logical framework

The present study follows the official definition of 'desertification' provided by UNCCD as a "*land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities*", that is in accordance with the notion of 'sensitivity to desertification' provided by Mediterranean Desertification and Land Use (MEDALUS) European project (Kosmas et al., 1999). This concept, originated from the debate on desertification risk in the Mediterranean basin, defines sensitivity as the state of a local system depending on the quality of vegetation, soil, climate and land management (Kosmas et al., 2000). The derived Environmental Sensitive Area (ESA) approach (Kosmas et al., 1999; Basso et al., 2000) has been used to assess the degree of soil and land sensitivity to degradation and desertification in Italy. This framework assures a (diachronic) assessment of changes in four analysis domains (soil, vegetation, climate and land management) considered as important factors related to degradation processes in the Mediterranean basin (e.g., Basso et al., 2000; Montanarella, 2007; Simeonakis et al., 2007). Using a multi-phase approach, the ESA procedure composes fourteen indicators into an index of soil and land sensitivity to degradation and desertification called Environmental Sensitive Area Index (ESAI). The main advantages of the ESA are the ease of use, the flexibility in choosing the input variables, and the efficiency of the land classification system based on its level of sensitivity to degradation (Ferrara et al., 2012). While possible drawbacks of this framework have been discussed in Basso et al. (2000), Salvati and Zitti (2009) and Salvati and Bajocco (2011), the ESA approach is one of the most frequently used and validated procedures to assess soil degradation and land sensitivity to desertification in the Mediterranean region (Salvati and Zitti, 2008; Bouhata and Kalla, 2014; Bakr et al., 2012; Symeonakis et al., 2015; among others). A regional study by Lavado Contador et al. (2009) has identified the ESAI as an indicator of soil degradation based on the correlation with a number of independent soil variables. Finally, Ferrara et al. (2012) has assessed the robustness of the ESA procedure and the performance of the ESAI in terms of insensitivity of spatial and temporal heterogeneity in the composing indicators.

Soil degradation is known as a complex phenomenon driven by multiple factors (Montanarella, 2007). Even if some of them could be underestimated or neglected in the ESA scheme (Salvati and Bajocco, 2011), in previous works it was demonstrated that – analyzing a larger number of candidate indicators of desertification (more than 50 variables linked to six distinct land degradation processes) – the distribution of vulnerable soil to degradation found in Italy at an enough detailed spatial scale is comparable to that obtained using the ESAI (Salvati et al., 2011). Correlations among candidate indicators have been also analyzed using multivariate statistical tools, and the analysis provided similar results to the one 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: (i) 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; (ii) soil depth and texture, slope and parent material as proxies for soil quality; (iii) fire risk, vegetation cover, protection from soil erosion and resistance to drought of land cover classes as proxies for vegetation quality; and (iv) population density, annual growth rate of population and intensity in the use of land as proxies for land-use quality. A detailed description of the considered variables and computing procedure was provided in previous studies (Kosmas et al., 1999, 2000; Basso et al., 2000; Salvati and Zitti, 2008).

At our knowledge, the considered layers are the most reliable, updatable and referenced data currently available in a Mediterranean country for the assessment of the ESAI at national or regional level (Salvati et al., 2011). However, comparable data required developing the full ESAI model with national coverage and detailed spatial scale was available at limited dates only. According to data availability, the level of soil degradation and land sensitivity to desertification were investigated at years 1960, 1990, 2000 and 2010 in Italy. All variables have been derived at the finest available spatial resolution (depending on the characteristics of each database, as detailed afterward) from official data sources including Corine Land Cover maps, meteorological statistics, population and agricultural censuses and the European Soil Database.

Climate variables were calculated on a ten-year base using information collected from the Italian Ministry of Agriculture Agrometeorological service. The database relates to gauging data collected daily from various meteorological and hydrological networks (Italian Air Force, Italian Ministry of Agriculture, National Hydrological Service and some minor networks) operating with nearly 3000 weather stations since 1951. Precipitation and temperature data (required to estimate the aridity index) were interpolated through kriging and cokriging procedures using elevation, latitude and distance to the sea as ancillary variables to ensure the complete national coverage (see Colantoni et al., 2015 for technical details). Average climatic values for 1960, 1990, 2000 and 2010 respectively refer to the time intervals 1951–1960, 1981–1990, 1991–2000 and 2001–2010. Aspect was derived by elaborating the ASTER global Digital Elevation Model at 30 m of resolution (Salvati and Bajocco, 2011) and soil data at 1 km^2 pixel resolution derived from the European Soil Database (JRC-Ispra). Ancillary information were derived from national databases of soil characteristics (Salvati and Zitti, 2008). Considering the length of the time span investigated, the aspect and used soil variables have been regarded to be static both because they change slowly or were not updated (Salvati and Zitti, 2009).

Vegetation variables derived from elaboration on two comparable maps: the CORINE-like 'Topographic and Land-use 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 (covering the 2010 time step). The maps were already used for multi-temporal analysis of land-use (see Salvati and Colantoni, 2015 among others) and other environmental indicators on a regional scale in Italy (Falcucci et al., 2007; Pelorosso et al., 2009; Salvati and Bajocco, 2011). Land management quality has been quantified as the result of population dynamics and selected land-use changes. Population data were derived from the National Censuses of Population carried out every ten years by the Italian National Institute of Statistics (see Istat, 2006 and the official web site: www.istat.it). Land-use intensity derived from the previously described maps.

The fourteen variables described below were transformed into sensitivity indicators using the ESA score system (Basso et al., 2000). This system (see Salvati and Bajocco, 2011 for a description of the scores assigned to each variable) uses scores ranging from 1 to 2 (lowest to highest sensitivity) to derive the contribution of each variable to the level of soil and land sensitivity to degradation. Scores are based on the estimated degree of correlation with independent field indicators measured in several pilot areas in southern Europe (Kosmas et al., 1999; Simeonakis et al., 2007; Lavado Contador et al., 2009).

2.4. Thematic indicators and the composite index

According to the ESA scheme (Kosmas et al., 1999), four thematic indicators (Soil Quality, Vegetation Quality, Climate Quality and land Management Quality Indices: SQI, VQI, CQI and MQI) assessing the four domains considered in the present study (soil, vegetation, climate and land-use/land management) have been calculated as the geometric mean of the individual variables transformed into environmental indicators of land sensitivity to degradation using the scores previously described. Indicators range from 1 to 2 (lowest to highest sensitivity). The ESAI was derived as the geometric mean of the four thematic indicators, thus ranging again from 1 to 2 (with the same meaning). All the layers of the ESAI maps were georeferenced to the 1 km elementary spatial unit by using ArcGIS software (ESRI Inc., Redwoods, USA). 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 sensitivity ('not affected' or 'potentially affected land': ESAI < 1.225, 'fragile land': $1.225 <$ ESAI < 1.375, and 'critical land': ESAI > 1.375).

Table 1
List of indicators considered in the present study and the related measurement unit.

Acronym	Indicator	Measurement unit
ESAI	Average Environmentally Sensitive Area Index by agricultural district	Score ranging from 1 to 2
ESAIv	Coefficient of variation in the ESAI score by agricultural district	Percentage
CQI	Average Climate Quality Index by agricultural district	Score ranging from 1 to 2
CQIv	Coefficient of variation in the CQI score by agricultural district	Percentage
SQI	Average Soil Quality Index by agricultural district	Score ranging from 1 to 2
SQIv	Coefficient of variation in the SQI score by agricultural district	Percentage
VQI	Average Vegetation Quality Index by agricultural district	Score ranging from 1 to 2
VQIv	Coefficient of variation in the VQI score by agricultural district	Percentage
MQI	Average land Management Quality Index by agricultural district	Score ranging from 1 to 2
%F	Surface land classified as 'fragile' (1.225 < ESAI < 1.375)	Percentage
%C	Surface land classified as 'critical' (ESAI > 1.375)	Percentage

2.5. Elementary data analysis

The analysis carried out on the 11 variables selected in the present study (see list in Table 1) is aimed at shedding light in the dynamic relationship between different factors (climate, soil, vegetation, land-use, anthropogenic pressure), underlying sensitivity to desertification in Italy and may illustrate the evolution of a CAS representing soil-landscape interactions over a long time interval (1960–2010). 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 each of the 773 agricultural districts identified by Istat (2006) on the base of homogeneous biophysical (topography, local climate, soil) and socioeconomic variables (prevailing crop systems, characteristics of the rural landscape, human settlements).

Homogeneous agricultural districts cover the whole national territory and allow for the analysis of changes in soil degradation and land sensitivity based on the four ESA 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 risk. Districts are considered a supra-municipal, sub-provincial homogeneous spatial unit illustrating the geography of rural areas and agro-forest systems in Italy (Salvati, 2013). Finally, agricultural districts in Italy represent economically relevant spatial units possibly indicating the impact of environmental policies adopted at both regional and local scales (Salvati and Zitti, 2008).

Additional indicators were calculated for the same points in time to describe the spatial variability of each thematic indicator and the composite index using CQI, SQI, VQI and ESAI Coefficients of Variations (CV) observed in each district and two supplementary indicators computing the share of 'fragile' and 'critical' land to the total surface area of each district for every investigated year. The MQI coefficient of variation was removed from further analysis in order to reduce multi-collinearity with the other CV indicators. The ESA scheme provides for an implicit standardization of variables and indicators (in both entity and direction) ranging from 1 to 2. This revealed useful in the subsequent analysis since it allows for full comparability among components.

2.6. Statistical analysis

Pair-wise correlations among the eleven indicators were checked at the beginning (1960) and the end (2010) of the study period using Spearman pair-wise non-parametric statistics testing for significance at $p < 0.05$ after Bonferroni's correction for multiple comparisons. The evolution of each agricultural district over time was studied through a Multiway Factor Analysis (MFA) applied to the eleven indicators measured at each time step (1960, 1990, 2000 and 2010). MFA can be considered an extension of the Principal Component Analysis (PCA) whose purpose is to analyze over time the changing structure of a set of variables collected on the same set of observations (Lavit et al., 1994). The general objectives of the MFA are: (i) to compare and analyze the relationship between the different data sets over time; (ii) to reveal, through a PCA, the common structure between the observations, and, finally, (iii) to analyze communalities and discrepancies by projecting the original data sets into a common structure called 'compromise' (Coppi and Bolasco, 1989). The absolute eigenvalue > 1 was used for selection of relevant factors (Salvati and Zitti, 2009).

The MFA allows evaluating if the position of each unit (i.e., indicator) or case (i.e., agricultural district) is stable or changing over time by projecting them into the same multivariate factor plane. This allows assessing the rapidity of change of both units and cases along the study period. A multivariate measure of rapidity of change for both MFA units (the eleven indicators) and cases (the 773 agricultural districts grouped into three geographical areas: northern Italy, central Italy and southern Italy) was provided as the linear distance between the factor loadings (or the factor scores) observed in t_1 and t_0 for each unit or case. The rapidity of change was investigated for each indicator and spatial unit during two time intervals (t_0: 1960–t_1: 1990 and t_0: 1990–t_1: 2010) representing different socioeconomic and territorial conditions in Italy (Istat, 2006) and over the whole study period (1960–2010). Relevant factors were selected according to the eigenvalue criterion illustrated above. For each geographical area, the rapidity of change (1960–2010) was correlated pair-wise with the ESAI at the beginning of the study period (1960) and with the percent change in the ESAI along the investigated time interval (1960–2010) using non-parametric Spearman correlation coefficients testing at $p < 0.05$. Both variables were taken as key factors influencing the evolutionary path of the system in the long term.

3. Results

3.1. Descriptive statistics of system's indicators

Based on the selected indicators (Table 2), the Italian agricultural districts experienced, on average, a progressive change in the degree of sensitivity to degradation over time. The composite index of land sensitivity (ESAI) grew significantly at the national level from 1.339 to 1.363 (Mann–Whitney non-parametric test assessing differences in the ESAI distribution between 1960 and 2010, $p < 0.05$, $n = 773$ districts) with a slight increase in the coefficient of spatial variability (ESAIv). The VQI showed a similar pattern with a marked increase between 1960 and 1990 (from 1.46 to 1.5) and a relatively stable sensitivity score in the most recent years. While the MQI decreased slowly,

Table 2
Average value for each indicator in Italy by year.

Variable	1960	1990	2000	2010
ESAI	1.339	1.352	1.359	1.363
ESAIv	0.039	0.046	0.046	0.046
CQI	1.107	1.173	1.193	1.178
CQIv	0.060	0.060	0.060	0.061
SQI	1.529			
SQIv	0.040			
VQI	1.462	1.500	1.499	1.500
VQIv	0.103	0.128	0.128	0.130
MQI	1.321	1.281	1.286	1.310
%F	19.4	29.3	30.3	31.5
%C	2.5	4.6	6.0	6.3

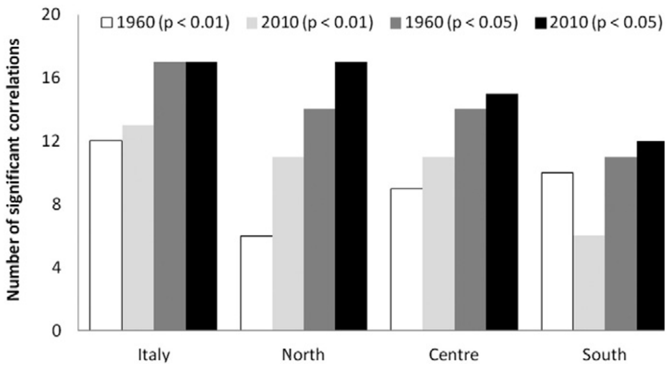

Fig. 1. Number of significant ($p < 0.05$ or $p < 0.01$; see Table 3) Spearman pair-wise correlation tests by geographical division and year.

the average CQI score grew rapidly from 1.107 to 1.193 – indicating a drier climatic regime observed between 1960 and 2000 – and then declined slightly to 1.178 in 2010. The coefficient of spatial variability increased moderately over time for all examined indicators. Based on these trends the share of 'fragile' land on total land grew from 19.5% in 1960 to 31.3% in 2010. A similar pattern was observed for the share of 'critical' land on total investigated land that increased from 2.5% to 6.3%.

3.2. Analyzing non-linear relationships between system's indicators

Results of non-parametric Spearman rank tests indicate that the number of significant pair-wise correlations among indicators increased between 1960 and 2010 in all geographical divisions of Italy (Fig. 1). By using two different significance thresholds ($p < 0.05$ and $p < 0.01$), northern and central Italy were characterized by the highest increase in the number of pair-wise correlations for both 1960 and 2010. The correlation matrix among indicators is reported in Table 3 by geographical division and year. In northern Italy, the ESAI increased with vegetation and land management quality in 1960 contributing to the growth of the surface area of 'fragile' land, with correlations increasing in 2010. In central Italy, the ESAI correlated with climate, vegetation and land management quality indexes in 1960. The correlation coefficients with all these quality indexes were found stable or moderately increasing in 2010. In southern Italy, only climate and vegetation quality increased significantly with the ESAI. The increased degree of sensitivity to desertification shown by the ESAI contributed to the expansion of 'fragile' and 'critical' land in both central and southern Italy.

3.3. The analysis of components' dynamics over time and space

The Multiway Factor Analysis applied to the eleven indicators for each study year extracted two factors with eigenvalue > 1 explaining 52% of the total variance. Table 4 shows the indicators' loadings to each factor. The number of significant loadings (>|0.6|) increased along factor 1 (3 and 5 significant loadings respectively in 1960 and 2010) being stable along factor 2 (2 significant loadings for both 1960 and 2010). This confirms the results gathered from the non-parametric correlation analysis which outlined the rising complexity in the relationship between system's indicators.

Factor 1 extracted 32% of the total variance, and it identifies a sensitivity gradient with the ESAI, the MQI and the share of 'fragile' land being the variables most associated to this component. The importance of the ESAI and the share of 'fragile' land along component 1 increased during the investigated time period, while MQI loadings maintained stable. VQI loadings increased over time being the highest in 2010 and a similar pattern was observed for the VQIv with loadings rising from 0.01 (1960) to 0.60 (2010). On the contrary, CQI loading decreased slightly along the first component passing from −0.54 (1960) to −0.47 (2010). The observed indicators' transition along factor 1 indicates the polarization in vulnerable and non-vulnerable areas across Italy as revealed by the increased loading of the ESAI, which was found positively correlated with both land management and vegetation quality. Factor 2 extracted 19.9% of the total variance and identifies a sensitivity gradient negatively associated with the average SQI and the spatial variability in the SQI (SQIv) for all the investigated years. The spatial variability in the ESAI (ESAIv) and in the VQI (VQIv) correlated negatively to this component with increasing loadings over time. Taken together, MFA components 1 and 2 illustrate the dynamics of the ESAI and the spatiotemporal relationship with the composing indicators (CQI, SQI, VQI and MQI) and their spatial variability.

Scores along factors 1 and 2 are illustrated in Fig. 2 separately for 1960 and 2010. In 1960, agricultural districts with negative scores along component 1 were concentrated in restricted areas of Sardinia, Emilia Romagna, Sicily and Apulia. The 2010 negative scores of some districts reflect the increase of their total number and size, and their sprawling along the Po plain, the Adriatic coast, the Tyrrhenian coast in central Italy as well as in areas of Apulia, Sicily and Sardinia regions. This consolidates a typical geography of land degradation in Italy associated to flat and coastal areas and characterized by high values of the ESAI, VQI and MQI (Salvati and Bajocco, 2011). Along factor 2, negative scores associated to low soil quality and higher land sensitivity to degradation were concentrated in the following districts: along the northern Apennine (indicating higher soil erosion risk), Tyrrhenian and Adriatic coasts (indicating higher soil salinization risk), Apulia and Basilicata regions (possibly indicating a higher vulnerability to soil compaction and sealing), and large areas of Sicily and southern Sardinia (being associated to a combination of the four degradation processes mentioned above).

By averaging the factor scores assigned by the MFA to each agricultural district in 1960, 1990, 2000 and 2010, Fig. 3 illustrates the temporal evolution of three geographical divisions of Italy (north, center, south) in the factorial plane formed by the two most relevant MFA factors. The three geographical divisions show differentiated patterns along both factors 1 and 2. While districts in northern and southern Italy moved rapidly along factor 1 towards neutral values respectively from the positive and negative scores observed in 1960, districts in central Italy moved along factor 1 from neutral to positive scores. Similar patterns were found along factor 2, with both northern and southern Italian districts converging towards neutral scores and central Italy scores being relatively stable over time. Taken together, the observed pattern indicates a convergence process characterizing districts in northern and southern Italy and a moderate divergence in land degradation for central Italy's districts.

3.4. Identifying 'fast' and 'slow' system's changes

Taken as an indirect measure of rapidity of change, the average annual distance among indicators or geographical divisions in the MFA plane (factors 1 and 2) during the time interval studied (1960–1990 and 1990–2010) was illustrated in Table 5. The indicators changing most rapidly in the first periods are the VQI (both average and coefficient of variation), the spatial variation in the ESAI (ESAIv) and the share of 'fragile' land (%F). In the most recent period, the rapidity of change of the ESAI, VQI and %F increased rapidly indicating the most dynamic variables within the investigated territorial system. The rapidity of change in the three geographical divisions of Italy was rather stable in the first period increasing in both northern and southern districts during the most recent period. Fig. 4 illustrates the position of each agricultural district in the factorial plane (factors 1 and 2) between 1960 and 2010. Taken together, agricultural districts in northern and southern Italy have showed the highest observed rapidity of change with special reference to districts in north-eastern Po valley (Veneto and Emilia Romagna regions), along the Adriatic coast and in southern Sicily. These

Table 3
Pair-wise Spearman rank correlation matrix between the investigated indicators by year and geographical division of Italy (bold and italics respectively indicate significant correlations at $p < 0.01$ and $p < 0.05$ after Bonferroni's correction for multiple comparisons).

1960

Italy	ESAvv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	0.20	**0.72**	0.08	0.19	0.05	**0.71**	0.18	**0.54**	**0.93**	**0.74**
ESAv		0.07	0.06	0.10	0.36	0.45	**0.78**	0.04	*0.42*	0.23
CQI			0.30	0.06	−0.02	*0.45*	0.03	0.13	**0.65**	**0.60**
CQIv				0.04	0.00	−0.01	−0.10	−0.04	0.05	0.12
SQI					*0.44*	0.02	0.06	−0.31	0.17	0.26
SQIv						0.12	0.26	−0.19	0.11	0.21
VQI							**0.53**	0.22	**0.75**	**0.52**
VQIv								−0.05	0.37	0.17
MQI									*0.46*	0.29
%F										**0.72**

Northern Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	0.30	*0.54*	−0.03	−0.17	−0.19	**0.68**	0.24	**0.82**	**0.89**	*0.53*
ESAIv		0.00	−0.05	−0.02	0.24	0.43	**0.75**	0.19	*0.59*	0.33
CQI			0.42	−0.37	−0.46	0.22	−0.13	*0.51*	0.45	0.36
CQIv				−0.10	−0.21	−0.18	−0.26	0.05	−0.06	−0.09
SQI					*0.59*	−0.22	0.06	*−0.54*	−0.14	−0.01
SQIv						0.00	0.23	−0.39	−0.08	0.00
VQI							0.57	0.41	**0.69**	0.33
VQIv								0.01	*0.50*	0.25
MQI									**0.68**	0.41
%F										*0.54*

Central Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	0.38	**0.66**	0.06	*0.55*	0.25	**0.70**	0.23	**0.64**	**0.92**	**0.71**
ESAv		0.28	0.04	0.14	0.41	*0.53*	**0.80**	0.05	*0.53*	0.31
CQI			0.29	0.29	0.16	0.42	0.21	0.20	**0.61**	*0.52*
CQIv				0.00	0.10	−0.09	−0.08	0.04	0.01	0.05
SQI					0.44	0.09	0.06	0.16	0.47	0.48
SQIv						0.05	0.20	0.10	0.26	0.35
VQI							*0.52*	0.28	**0.73**	0.43
VQIv								−0.17	0.37	0.13
MQI									*0.55*	0.47
%F										**0.68**

Southern Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	−0.07	**0.72**	0.14	0.20	0.06	**0.73**	−0.06	0.46	**0.93**	**0.87**
ESAvv		−0.16	0.24	0.18	0.29	0.28	**0.65**	−0.19	0.08	0.06
CQI			0.22	−0.07	0.01	*0.51*	−0.12	−0.03	**0.60**	**0.68**
CQIv				0.15	0.15	0.20	0.06	−0.14	0.12	0.25
SQI					0.21	0.16	0.01	−0.11	0.15	0.24
SQIv						0.15	0.09	−0.02	0.04	0.21
VQI							0.31	0.06	**0.75**	**0.66**
VQIv								−0.15	0.05	−0.01
MQI									0.42	0.32
%F										**0.78**

2010

Italy	ESAvv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	−0.24	**0.62**	0.02	0.02	−0.08	**0.79**	*−0.40*	**0.68**	**0.91**	**0.84**
ESAvv		−0.04	0.15	0.10	0.30	−0.26	**0.83**	−0.15	−0.17	0.03
CQI			0.12	0.14	0.05	0.21	−0.06	0.15	**0.52**	**0.67**
CQIv				0.09	−0.02	−0.07	0.05	0.04	0.00	0.11
SQI					*0.44*	−0.26	0.10	−0.32	−0.07	0.17
SQIv						−0.12	0.21	−0.23	−0.09	0.09
VQI							*−0.47*	**0.58**	**0.81**	*0.48*
VQIv								−0.27	−0.36	−0.13
MQI									**0.64**	**0.52**
%F										**0.69**

Northern Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	−0.35	*0.51*	−0.13	−0.33	−0.37	**0.87**	*−0.51*	**0.83**	**0.93**	**0.76**
ESAv		−0.15	0.20	0.07	0.34	−0.45	**0.90**	−0.15	−0.27	−0.08
CQI			0.11	−0.15	−0.22	0.27	−0.18	0.32	0.44	*0.54*
CQIv				−0.04	−0.17	−0.23	0.15	0.00	−0.12	0.02
SQI					*0.59*	−0.43	0.16	*−0.58*	−0.39	−0.16
SQIv						−0.35	0.32	−0.47	−0.36	−0.20
VQI							**−0.61**	**0.67**	**0.85**	*0.53*
VQIv								−0.32	−0.43	−0.22
MQI									**0.82**	**0.72**
%F										**0.71**

Central Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	−0.12	**0.69**	0.32	0.48	0.25	**0.75**	−0.33	**0.86**	**0.91**	**0.89**
ESAvv		−0.12	−0.02	−0.16	0.10	−0.05	**0.69**	−0.05	−0.03	−0.06
CQI			0.40	0.47	0.29	0.24	−0.12	*0.52*	*0.56*	**0.72**
CQIv				0.14	0.12	0.14	−0.13	0.31	0.24	0.33
SQI					0.44	0.16	−0.21	0.16	0.41	0.49
SQIv						0.17	−0.02	0.07	0.24	0.31
VQI							−0.38	*0.57*	**0.79**	*0.52*
VQIv								−0.21	−0.33	−0.26
MQI									**0.77**	**0.79**
%F										**0.76**

Southern Italy	ESAv	CQI	CQIv	SQI	SQIv	VQI	VQIv	MQI	%F	%C
ESAI	−0.39	*0.58*	0.00	0.12	0.03	**0.77**	*−0.57*	0.37	**0.82**	**0.86**
ESAv		−0.19	0.23	0.16	0.18	−0.31	**0.77**	−0.23	−0.34	−0.08
CQI			0.02	−0.11	−0.05	0.24	−0.24	−0.16	0.38	**0.61**
CQIv				0.19	0.13	0.08	0.07	−0.07	−0.02	0.07
SQI					0.21	−0.01	0.05	−0.12	0.01	0.22
SQIv						0.14	−0.02	−0.01	0.03	0.13
VQI							*−0.55*	0.29	**0.81**	*0.53*
VQIv								−0.29	*−0.57*	−0.30
MQI									0.30	0.25
%F										*0.56*

Table 4
Multiway Factor Analysis loadings by year and indicator (significant loadings > |0.6| are marked in bold).

Variable	Factor 1				Factor 2			
	1960	1990	2000	2010	1960	1990	2000	2010
ESAI	**−0.81**	**−0.93**	**−0.92**	**−0.93**	−0.46	−0.26	−0.29	−0.14
ESAIv	−0.02	0.40	0.40	0.45	−0.44	−0.59	−0.57	−0.52
CQI	−0.54	−0.52	−0.47	−0.47	−0.46	−0.52	−0.56	−0.47
CQIv	0.08	0.16	0.20	0.16	−0.29	−0.27	−0.25	−0.25
SQI	0.10	0.10	0.10	0.10	**−0.66**	**−0.66**	**−0.66**	**−0.66**
SQIv	0.18	0.18	0.18	0.18	**−0.66**	**−0.66**	**−0.66**	**−0.66**
VQI	−0.59	**−0.84**	**−0.84**	**−0.85**	−0.34	0.17	0.17	0.15
VQIv	0.01	0.59	0.58	**0.60**	−0.37	−0.51	−0.51	−0.50
MQI	**−0.63**	**−0.60**	**−0.62**	**−0.63**	0.24	0.22	0.24	0.31
%F	**−0.73**	**−0.88**	**−0.86**	**−0.87**	−0.41	−0.04	0.00	0.04
%C	−0.44	−0.54	−0.57	−0.58	−0.48	−0.53	−0.54	−0.29
% explained variance				31.8				19.9

districts are classified as rapidly changing (i.e., 'fast' local systems) in contrast with the more stable (i.e., 'slow' local systems) districts found in northern Italy (Trentino Alto Adige, Piedmont and Emilia Romagna Apennine area), southern Italian Apennine region and northern Sardinia.

3.5. The correlation between rapidity of change and sensitivity to land degradation

Fig. 5 illustrates the relationship observed between the multivariate distance (1960–2010) in the MFA plane (factors 1 and 2) taken as a measure of rapidity of change and the level of the ESA index taken as a proxy of soil degradation and land sensitivity to desertification measured for each district at the beginning of the study period (1960) or the percent change in the level of the ESAI during the whole time interval (1960–2010). In both northern and central Italy, local districts' rapidity of change was not correlated with the level of land sensitivity in 1960 while a negative correlation was observed in southern Italy ($r_s = 0.64$, $p < 0.001$). The correlation between changes in the ESAI (1960–2010) and district's rapidity of change was positive in northern Italy ($r_s = 0.64$, $p < 0.001$) and central Italy ($r_s = 0.51$, $p < 0.005$) and negative in southern Italy ($r_s = -0.43$, $p < 0.05$). These findings indicate diverging environmental changes in the three divisions of Italy.

4. Discussion

Environmental quality and ecological risk are becoming key concepts that refer jointly to economic dynamics, social change and political action. Soil and landscape degradation, taken as a key process of environmental degradation in southern Europe, are clear examples of the interaction between the socio-ecological and the economic-institutional systems. While sustainability has intended, for a long time, to reconcile growth with environmental quality (e.g., Zuindeau, 2006; Nader et al., 2008), Mediterranean socio-environmental systems involve more complex aspects from both sides of the relationship incorporating social, cultural and political factors (Wilson, 2014).

From a socioeconomic point of view, problems related to unbalanced natural and physical resources, economic polarization and socio-spatial divergences along the Mediterranean region are crucial when addressing the evolution of a complex soil–landscape system. While human misuse of land was recognized as one of the most relevant causes of soil degradation (Salvati and Zitti, 2008), the anthropogenic drivers of (and the local context characterizing) soil degradation require investigation through integrated and multidisciplinary approaches aimed at monitoring their long-run impact. Together with socioeconomic disparities, multi-level policy responses to desertification should address system complexity and the spatially heterogeneous distribution of the natural capital. Studies dealing with the recognition, quantification and spatial representation of complex environmental phenomena (Thornes, 2004; Ibanez et al., 2008; Salvati et al., 2011) indicate that land degradation monitoring may benefit from multi-dimensional approaches focusing on the (evolving) relationship among elementary components. Nevertheless, several interacting variables can be included in models exploring the complexity of socio-ecological systems. The analysis of socio-ecological systems requires computational approaches supporting environmental policies with a coherent information base. According to the Complex Adaptive Systems framework, the approach proposed in the present study considers both soil degradation and land sensitivity to desertification as a dynamic process evolving under non-linear feedback interactions among components. Eleven indicators were tested as proxies of different system's components changing over space and time in 773 agricultural districts, considered a spatially detailed and socio-ecologically consistent analysis domain in Italy.

The multivariate analysis developed here interpreted system's complexity in terms of spatiotemporal evolutionary path and non-linear feedback mechanisms among relevant components. Our procedure represents a simplified logical framework that can be applied to other highly dynamic socio-ecological systems. By adopting a framework based on Complex Adaptive Systems, the illustrated methodology goes beyond the collection of environmental indicators or the application of computational techniques to derive simple composite indexes of soil/land sensitivity to desertification. Instead, starting from well-known and easily accessible variables composing the standard environmental ESA index (Basso et al., 2000), the methodology introduced a procedure simulating the main characteristics of a soil–landscape CAS under progressive degradation phenomena. The procedure may integrate and analyze a large number of components including institutional, social and economic variables. Model outcomes allow evaluating the whole system complexity, the distinctive latent patterns and its spatio-temporal dynamics.

Our results indicate that the number of pair-wise significant correlations among system's components increases with the level of land sensitivity to desertification. This finding suggests that more complex systems (i.e., relationships among components) tend to become more sensitive (Abson et al., 2012); environmental policies should recognize this dynamic interplay as a key target for improved measures against soil degradation (Juntti and Wilson, 2005). Complex systems could also be able to resist to external stress and to reorganize more rapidly after prolonged shocks. Moreover, the rapidity of change in both indicators and agricultural districts varied according with the level of sensitivity to desertification typical of each local context. This may confirm the convergence/divergence processes in the level of soil–landscape degradation observed in previous studies (Salvati and Zitti, 2008) and allows identifying the components contributing the most to the evolution of each local system.

Soil and vegetation are the components mostly associated to equilibrium conditions on a local scale (see also Simeonakis et al., 2007). Poor soil quality and scarce vegetation cover are the attributes most typically associated with strongly imbalanced socio-ecological settings. This suggests how place-specific measures dealing with soil degradation and the role of natural vegetation (e.g., protecting from fires, overgrazing or urbanization) could be important in achieving equilibrium conditions, possibly reducing spatial disparities in the quality of natural resources (e.g., Zuindeau, 2006).

Studies like the present one have both positive (i.e., research) and normative (i.e., policy) implications (Stringer et al., 2013). From the research perspective, the flexibility and comprehensiveness of the approach illustrated may contribute to the urgent need of implementing diachronic and multi-dimensional approaches for soil degradation and desertification at adequate spatial resolution, providing basic information to develop short-term risk scenarios (Salvati and Zitti, 2008). At the same time, environmental policies should address multiplex economic, social and environmental targets to ensure long-term sustainability.

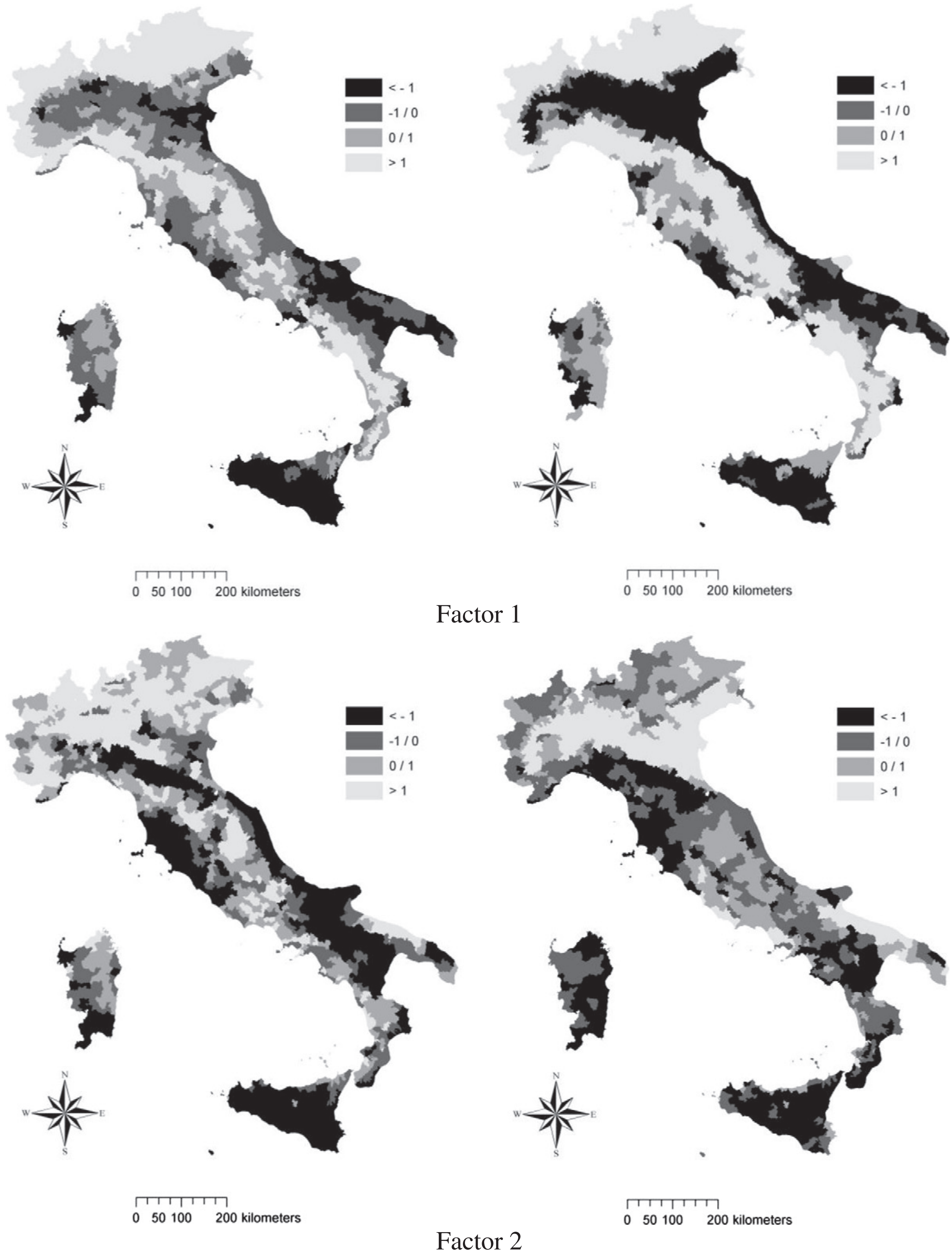

Fig. 2. Maps of factor 1 and 2 scores by agricultural district and year (left: 1960, right: 2010).

In this sense, our approach provides a multi-temporal assessment of complex and dynamic systems with the aim to inform sustainable land management strategies (Imeson, 2012). Achievements in this issue will allow: (i) to fill the gap due to the incomplete communication among the different policy levels (local, national, international); (ii) to monitor the effects of policy and management options through context-specificity analyses in affected areas; (iii) to make available a multi-scale, comprehensive framework assessing soil degradation and land desertification problems; and, finally, (iv) to shed light on the interactions between components and drivers reflecting the multiplicity of the socio-ecological systems, at regional and country scale.

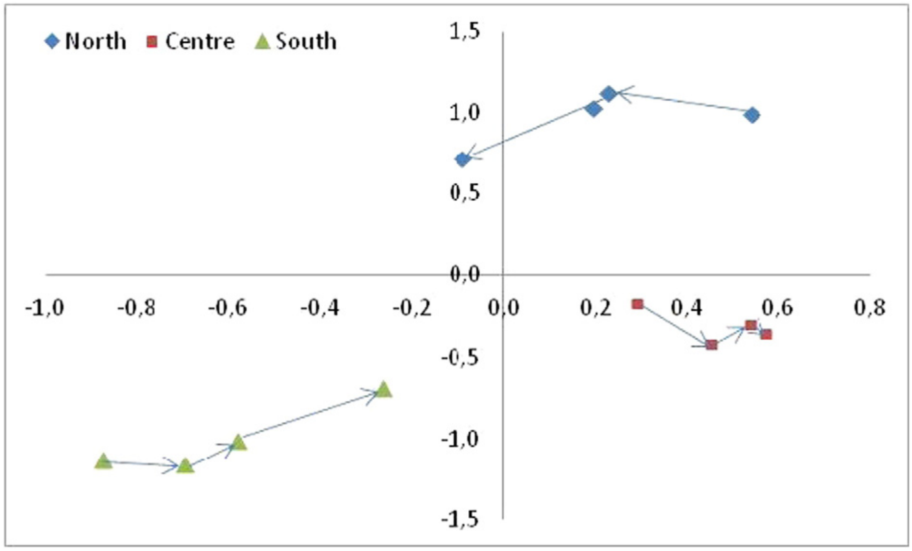

Fig. 3. Multiway factor score plot by year and geographical division.

Managing land in a sustainable manner means using land without damaging ecological processes or reducing biological diversity. It requires the maintenance of key components of the environment, such as biodiversity, ecological integrity and natural capital as well as the conservation of a rich set of relationships among the constituting elements of the system. At the landscape level, the conservation of productive forest areas and potentially commercial and non-commercial forest reserves (Carmona and Nahuelhual, 2012), the maintenance of the integrity of watersheds for water supply and hydropower generation needs and the capability of aquifers to serve farm and other productive activities are possible examples of the complexity and fragility of territorial systems (Simeonakis et al., 2007). The relevance of sustainable land management practices to reverse or mitigate soil degradation processes and land misuse is widely demonstrated. Sustainable land management is a straightforward tool not only for the recovery of arid land, but also to the conservation of sensitive – but not degraded – areas where pressure from the resident population is potentially severe and where the long-term consequences of landscape degradation or unsustainable management of land became progressively serious.

5. Conclusions

Results of our study inform regional policy developing thematic and multi-scale strategies for the mitigation of soil degradation. Outcomes of the present study represent a useful example for the assessment of complex local systems' dynamics in countries characterized by territorial disparities in socioeconomic and environmental variables. The approach allows an objective and easy identification of 'fast' and 'slow' factors underlying soil and landscape degradation as well as 'rapidly-evolving' or 'locked' local systems according to the rapidity of change of each constituting element of the system.

Table 5
Rapidity of change (i.e., standardized average annual distance) among indicators' or cases' points in the MFA plane formed by the two main factors by time interval.

	1960–1990	1990–2010	1960–2010
Indicator			
ESAI	0.08	0.16	0.07
ESAIv	0.15	0.05	0.10
CQI	0.02	0.03	0.01
CQIv	0.03	0.02	0.02
SQI	0.00	0.00	0.00
SQIv	0.00	0.00	0.00
VQI	0.19	0.25	0.11
VQIv	0.20	0.07	0.12
MQI	0.01	0.04	0.01
%F	0.13	0.23	0.09
%C	0.04	0.10	0.05
Geographical division			
North	0.12	0.21	0.14
Center	0.10	0.07	0.05
South	0.11	0.23	0.15

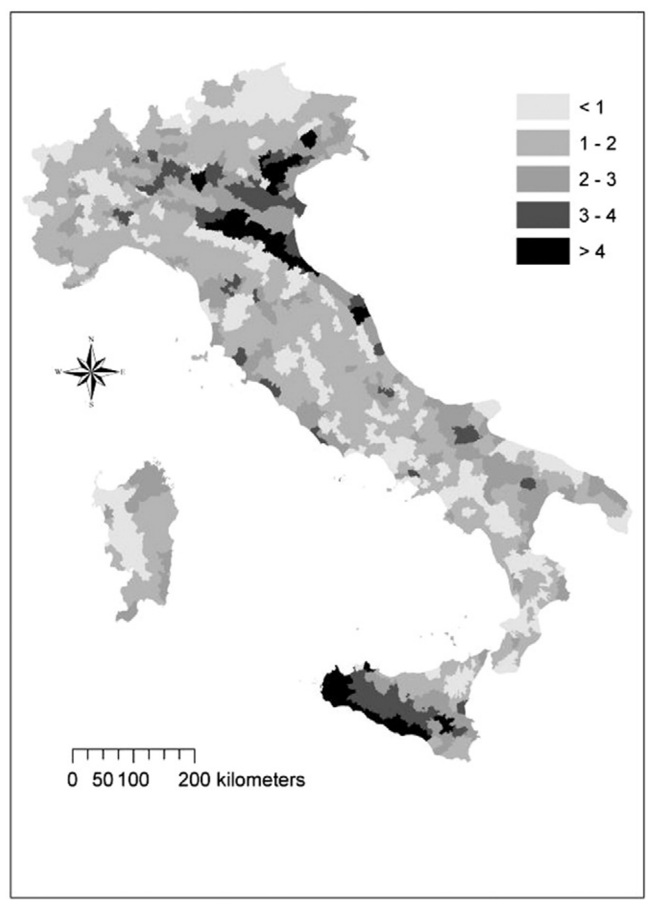

Fig. 4. The multivariate distance between the position of each agricultural district in the factorial plane (factors 1 and 2) in 1960 and in 2010.

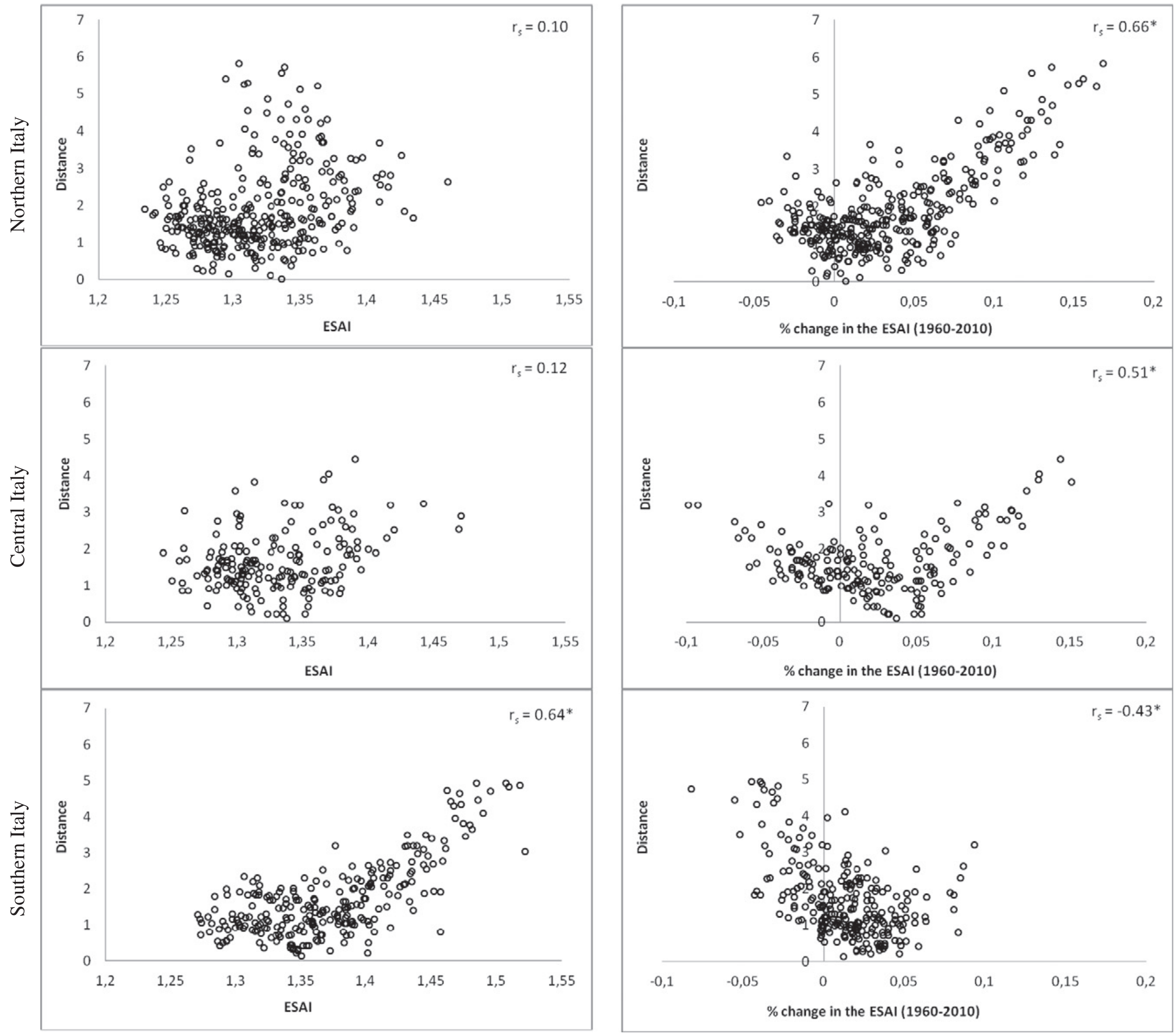

Fig. 5. The relationship between the multivariate distance taken as a measure of rapidity-of-change observed for each agricultural district during 1960–2010 (see text for details) and the average ESAI measured in 1960 (left) or the percent change in the ESAI between 1960 and 2010 (right) by geographical division in Italy (* indicates significant Spearman correlation at $p < 0.05$).

However, despite the reliability of quantitative and modeling approaches to system's complexity, other approaches integrating the information derived from quantitative frameworks with narrative studies seem to be relevant. In fact, the intimate relation among several variables and factors is difficult to measure due to omitted variables. Soil degradation patterns and desertification risk in southern Europe can be thus effectively monitored using a mixed quali-quantitative approach describing, through story-line narratives and other informative supports, the evolutionary path of each local system. These tools may provide a more reliable and complete view of socio-ecological systems whose complexity, path-dependence, and rapidity of change are hardly addressed solely with quantitative methods. The methodology and the analysis' exercise proposed in this paper should be considered as a first contribution to a more articulated, quali-quantitative framework assessing soil degradation and land sensitivity to desertification and informing sustainable land management policies.

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