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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