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Towards a process-based evaluation of land vulnerability to soil degradation in Italy

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ABSTRACT

This paper illustrates a process-based approach aimed at classifying large areas into different classes of vulnerability to Mediterranean land and soil degradation (LD and SD). A wide set of environmental and socio-economic variables was used to describe five soil degradation processes (soil erosion, salinisation, sealing, contamination, and compaction) and climate taken together as the final determinants of LD in Italy. The elementary variables contributed to generate six thematic indicators which depict the level of vulnerability of the country to each degradation process. The Multivariate Soil Degradation Vulnerability Index (MSDVI) provided an estimation of the level of land vulnerability by aggregating the six indicators. Multidimensional analyses and Geographic Information System tools were used to derive the thematic indicators and the synthetic index. Results demonstrated that in Italy, climate, soil erosion, and soil compaction/agricultural intensification represent the soil degradation processes with a potentially higher role in determining vulnerability to LD, even if with different spatial configuration patterns. On average, the most vulnerable area was insular Italy, followed by southern Italy; northern and central Italy were found less vulnerable to LD, however the MSDVI was found locally high also in northern Italy. The validation tests performed on MSDVI by field assessment and comparison with ancillary data indicated that the index is a reliable proxy of land vulnerability to soil degradation. Advantages of this approach compared to other procedures aimed at assessing LD were finally discussed.

1. Introduction

Land degradation (LD) is a global process known to be active especially in arid, semi-arid and dry sub-humid areas. It was regarded as the result of various factors, including climatic variations and human activities, and it progressively leads to a reduction of the soil fertility, which represents a phenomenon commonly regarded as a soil degradation (SD) process (Jie et al., 2002; Fullen, 2003). The complexity of the environmental processes involved in LD is particularly evident in the Mediterranean countries due to the long-term interaction between bio-physical and socio-economic phenomena (Puigdefábregas and Mendizabal, 1998). According to the last estimates available for this area, soil vulnerability has increased in recent years due to the synergic action of climate aridity, land cover changes, and human pressure (Mairota et al., 1998; Bajocco et al., 2010).

When dealing with a degrading landscape, monitoring strategies should be the major research component and the underlying measurement concepts should encompass the multi-disciplinary perspectives of the problem (Reynolds and Stafford Smith, 2002; Gisladottir and Stocking, 2005; Grainger, 2009). Reflecting the complexity of the involved factors, much information exists on SD, LD, and desertification. Accordingly, a number of recent studies has been carried out and different methodologies have been proposed for assessing SD and LD making use of visual observation, field measurements, social enquiries, environmental indicators derived from statistical sources, remote sensing, and mathematical models (Basso et al., 2000; D'Angelo et al., 2000; Bathurst et al., 2003; Gad and Lotfy, 2008). There is a risk, however, of being overloaded with data and missing some key messages conveyed by the changing landscape. In this sense, environmental indicators have the advantage of (i) being rather simplified to be computed, (ii) producing synthetic information on the state and temporal evolution of multifaceted phenomena, and (iii) being easily communicable to both stakeholders and policy-makers. These indicators ensure the most effective use of the available data (Kosmas et al., 2003; Rubio and Recatala, 2006) and, furthermore, can be used as simplified inputs to a Decision Support System (e.g. D'Angelo et al., 2000).

Among the indicator-based procedures aimed at quantifying the land surface exposed to degradation, the standard Environmentally Sensitive Area (ESA) framework is the most frequently applied in the Mediterranean basin due to its simplicity in model building and its flexibility in the use of several variables (Brandt, 2005).

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In this model, different factors (climate, soil, and vegetation) produce a synthetic index of land sensitivity, the so-called ESAI (Lavado Contador et al., 2008). Additional factors have been proposed in further studies to take into account the impact of the human pressure (Rubio and Bochet, 1998; Basso et al., 2000; Leemans, 2008). Such factors are based on proxies for the quality of land management and the intensity of land exploitation by the agriculture.

Other ESAI-like indexes of LD risk introduced time-series multivariate analyses of a set of indicators that estimates the level of land vulnerability through an objective weighting system (Villa and McLeod, 2002; Salvati et al., 2009; Santini et al., 2010). The majority of these studies, however, generates indicators that are suited for early-warning purposes rather than concentrating on the processes behind LD. Improvements in this direction may thus strengthen the traditional ESA approach by estimating the actual level of vulnerability to specific *soil* degradation processes. Knowledge of the basic processes determining the level of the soil vulnerability of a certain area contributes to the assessment of LD and is crucial in planning effective policies against desertification (Helldén, 1991; Lambin et al., 2001; Silleos et al., 2008).

The objective of this paper is hence to illustrate and validate a process-based evaluation of land vulnerability to soil degradation over the entire Italy, and hence to propose a synthetic index based on the statistical combination of several socio-economic and biophysical indicators of soil degradation processes. Finally, the paper discusses the use of the proposed methodology as a potentially independent procedure, that can be considered ancillary to the ESA approach and designed for regional LD analysis and policy implementation at large scale.

2. Methods

2.1. Logical framework

Despite the considerable number of issues at stake, so far investigations on Mediterranean LD and SD were mostly based on qualitative or semi-quantitative methods (Montanarella, 2007). Many of them used elementary indicators to build-up a final index of land sensitivity. The aim is hence to overcome the methodological constraints of these procedures, including the subjectivity in the choice of the significant indicators and their weighting systems.

We thus considered the five soil degradation processes that have been recognized as the most representative in Mediterranean LD (Montanarella, 2007; Costantini et al., 2009): soil sealing, soil salinisation, soil erosion, soil contamination, and soil compaction/agricultural intensification (Eckelmann et al., 2006; Kibblewhite et al., 2007). We added a sixth theme related to climate since its impact on soil vulnerability is going to increase and it is only partially included in the above mentioned processes (Sivakumar, 2007). A number of factors were thus chosen in order to depict (directly or indirectly) the indicators corresponding to the six degradation processes (Table 1).

From the computation point of view, this work is based on the original multivariate approach illustrated in Salvati et al. (2009) to derive the weights to assign to each selected indicator, and extended it to the six SD processes considered here. The procedure retains the advantages of ESAI of being simplified, modular, and flexible. Besides, it quantifies the level of soil vulnerability to each degradation process through thematic indicators and further aggregates them into a synthetic index named the Multivariate Soil Degradation Vulnerability Index (MSDVI).

2.2. Data and indicators

Thirty-seven variables covering the six degradation systems (five concerning soil sealing, twelve for soil erosion, four covering soil salinisation, one for soil contamination, five concerning soil compaction and agricultural intensification and, finally, ten quantifying the climate quality) were selected.

Since land cover reflects the structural state of the real landscape (including the effects of human activity on the biophysical unit), many thematic indicators of this study used variables derived from the CORINE (Coordinated Information on the European Environment) Land Cover (CLC) project. It was aimed at providing land cover maps at various times for the whole of Europe and was coordinated by the European Environment Agency (EEA). The CLC inventory is based on satellite images as the primary information source. The choice of scale (1:100,000), minimum mapping unit (MMU) (25 ha) and minimum width of linear elements (100 m) for CLC mapping represents a trade-off between production costs and level of detail of land cover information (EEA, 2007). The standard CLC nomenclature includes 44 land cover classes, grouped in a three-level hierarchy. The CLC products are the most recent and comparable data on land cover for Italy.

The elementary variables and the corresponding thematic indicators used in this study (Table 1) are described in the following paragraph according to the degradation process to which they contribute. If not differently stated, all variables refer to 2000 or 2001.

2.2.1. Soil sealing

The multifaceted environmental impact of the anthropogenic pressure sources is very relevant in southern Europe, because it is directly related to demographic dynamics, economic development, social changes, diffusion of human settlements, and infrastructures, phenomena leading to landscape fragmentation, and indirectly causing soil pollution risk from diffused and point (Salvati and Zitti, 2005; Ceccarelli et al., 2006). In particular increases in tourism, population density, and urban growth, represent the main drivers of LD in highly anthropogenic landscapes; this is mainly due to the worsening impact connected with the consequent increase in soil sealing.

Five variables were calculated at the municipal level or at a lower scale (e.g. building block) when available, and included population density (POP) and growth (GRW), the proportion of built-up areas (URB), the concentration of population in compact urban centres (SET), and tourism density (TOU). All variables were calculated from the National Censuses of Population, Buildings and Industry carried out by the Italian National Statistics Institute (Istat) and from the CORINE land cover maps provided by the Italian National High Institute for Environmental Research and Protection (Ispra).

2.2.2. Soil salinisation

The salinisation of the soil is a process by which water-soluble salts (sodium, magnesium, calcium, chloride, sulphate, carbonate, and bicarbonate) accumulate in the soil reducing its fertility. Salt in soils decreases the osmotic potential of the soil so that plants find progressively difficult to take up water from it. Salts can also have a direct effect being toxic for plants: the consequence is a serious reduction of soil fertility. Salinisation may occur naturally (primary salinisation) or due to unsustainable management practices (Van-Camp et al., 2004). Since there are limited and localized field data quantifying these processes, proxies are generally used for the definition of areas exposed to salinisation risk (Costantini et al., 2009). In this work four variables were used including the surface areas exposed to primary salinisation (determined by a spatial intersection between the Geological Map of Italy at the 1:500,000 scale and the distance from the sea coast) (SAL), the percent surface area of farms practicing groundwater irrigation (GRO) and equipped with obsolete irrigation systems (IRR) on the total agricultural surface area. The Shannon index applied to irrigated farm data was finally used to estimate the diversification of the irrigation sources used by the Italian farms (DIV). The last three variables were calculated at

Table 1
List of the elementary variables considered in this study aggregated by soil degradation process and theme partition ('happy' or 'sad' smileys represent respectively positive o negative linkage between the variable and LD).

Soil degradation process	Theme partition	Variable	Link with LD	Code	Unit of measure	Source	Spatial unit
Soil sealing	Population	Population density	☹	POP	People/km^2	National Census of Population	Municipality
		Annual population growth	U	GRW	%	National Census of Population	Municipality
		Density of workers in tourism sector	☹	TOU	People/km^2	National Census of Buildings	Municipality
	Urbanization	Urban surface area/total municipal area	☹	URB	%	CORINE land cover map	Municipality
		People living in compact settlements	☹	SET	%	National Census of Services	Municipality
Soil erosion	Soil properties	Soil depth	☺	DEP	mm	Various	1:250,000
		Soil texture	😐	TEX	Sensitivity score	Various	1:250,000
		Maximum available water capacity	☺	AWC	mm	Various	1:250,000
		Soil parent material	😐	PAR	Sensitivity score	Various	1:250,000
		Potential risk index of erosion by water	☹	ERO	ton/ha/year	JRC	1:250,000
	Land cover and management	Drought resistance index	☺	DRE	Sensitivity score	CORINE land cover map	1:100,000
		Fire risk index	☹	FRE	Sensitivity score	CORINE land cover map	1:100,000
		Erosion protection index	☺	EPR	Sensitivity score	CORINE land cover map	1:100,000
		Vegetation cover index	☺	VEG	Sensitivity score	CORINE land cover map	1:100,000
		Grazing index	☹	GRA	Animals/ha	National Census of Agriculture	Municipality
		Wooded burnt surface area/total woodland surface	☹	BUR	%	Fire statistics	Municipality
		Protected areas/total municipal area	☹	PRO	%	Ministry of the Environment	Municipality
Soil salinisation	Primary salinisation	Areas with primary salinisation risk	☹	SAL	Sensitivity score	Various	1:250,000
	Secondary salinisation	Farms exploiting groundwater irrigation/total farms	☹	GRO	%	National Census of Agriculture	Municipality
		Farms with obsolete irrigation systems/total farms	☹	IRR	%	National Census of Agriculture	Municipality
		Diversification of the irrigation sources	☺	DIV	Shannon index	National Census of Agriculture	Municipality
Soil contamination	Pollution	Contamination footprint	☹	CON	Cont. units/km^2	All national censuses	Municipality
Soil compaction/ agriculture intensification	Agricultural land use	Crop intensity index	☹	INT	%	National Census of Agriculture	Municipality
		Soil compaction risk index	☹	COM	Machines/km^2	National Census of Agriculture	Municipality
		Change in the agricultural land surface (1990–2000)	U	LOS	%	National Census of Agriculture	Municipality
	Farm management	Surface area of farms granted in leasing/total farm surface	☹	AFF	%	National Census of Agriculture	Municipality
		Farmers older than 55 years/total farmers	☹	AGE	%	National Census of Agriculture	Municipality
Climate quality	Precipitation	Average year rainfall	☺	PRE	mm	CRA-CMA	1:400,000
		Rainfall seasonality index	☹	PST	mm/mm	CRA-CMA	1:400,000
		Rainfall concentration index	☹	PCO	mm/day	CRA-CMA	1:400,000
		Rainfall variability index	☹	PVA	%	CRA-CMA	1:400,000
		SPI drought index	☺	SPI	Sensitivity score	CRA-CMA	1:400,000
		Soil moisture	☹	MOI	mm	CRA-CMA	1:400,000
	Temperature	Dry spells period	☺	SPE	Day	CRA-CMA	1:400,000
		Occurrence of high temperature ($T > 35\,^{\circ}$C)	☺	TEM	%	CRA-CMA	1:400,000
		Aridity index	☺	ARI	mm/mm	CRA-CMA	1:400,000
		Slope exposure angle	☹	ANG	Degree	CRA-CMA	1:400,000

the municipal level based on data provided by the National Census of Agriculture.

2.2.3. Soil erosion

Erosion of the soil can be considered as a striking process of degradation and its natural rate usually increases due to unsustainable human activities and climate change (Verheijena et al., 2009). As soil formation is a very slow process, high soil loss can have serious effects, both on- and off-site. Due to the lack of homogeneous field measures covering the entire Italy, we used a set of twelve variables regarded as *proxies* for the process of soil erosion mainly due to the impact of water on soil. These are related to four themes: soil properties, natural vegetation and crop cover, anthropogenic pressures, and soil protection measures.

Soil properties include depth (DEP), texture (TEX), parental material (PAR), and the potential (maximum) water capacity of the agricultural soils (AWC) (Kosmas et al., 2003). The maps produced by the Italian National Centre of Pedological Cartography were considered as the representative data source. Additional information were gathered from the European Soil Map produced by the Joint Research Centre (JRC). The variables referring to the last three themes were derived from the CORINE land cover map, the map of soil erosion risk produced by the JRC, and the National Censuses of Agriculture and Population. They include an indicator of potential erosion risk estimating the annual soil loss (ERO) by using the USLE methodology (Salvati et al., 2009), a drought resistance indicator (DRE), the rate of vegetation cover (VEG), and two additional indicators quantifying fire risk (FRE) and the vegetation protection against soil erosion (EPR). The last four indicators were obtained by reclassifying the CORINE land cover map following the MEDALUS procedure (Basso et al., 2000). According to Kosmas et al. (2000), a weight was attributed to each land cover category in order to obtain a classification of the territory based on the different levels of sensitivity of its vegetation and landscape characteristics (Brandt, 2005).

Variables quantifying forest fires as the percentage of burnt surface area on the total forested surface area (BUR), overgrazing (GRA) as the ratio of an indicator of livestock pressure (Salvati et al., 2007) to the available grassland surface area, and the percentage of surface areas under environmental protection (PRO) were lastly calculated at the municipal scale.

2.2.4. Soil contamination

Soil contamination represents a severe hazard for soil quality and may be produced *on-site* or by diffused sources due to growing population (e.g. urban wastewater contaminated by organic substances or chemical agents), agriculture (e.g. fertilizers, pesticides, livestock wastes), industry, mining, and landfills; only in few cases environmental restoration leads to a complete recovery of soil functionality. In spite of the role of soil contamination on LD, the availability of homogeneous and reliable datasets at the national level is restricted. In order to overcome this constraint, soil contamination due to the human activities was evaluated according to Barbiero et al. (1998). This estimation, that we regarded as a ‘contamination footprint’ (CON), considered three components: resident population, agriculture (including livestock), and the industrial activities. All these activities were classified by scores according to their potential impact on soil quality. The sum of the scores divided by the municipality surface area quantifies the ‘contamination footprint’ variable in each Italian municipality (Salvati and Zitti, 2005).

2.2.5. Soil compaction and agricultural intensification

Environmental hazards from agriculture are mainly caused by the unsustainable management of land which is often market-induced (Shortle and Abler, 1999). On one hand, where the natural resources are relatively abundant and the technologies are easily available, a progressive crop intensification can be observed with associated risk of soil resource overexploitation. On the other hand, when conditions of depopulation and marginalisation take place, the consequent abandonment of lands may contribute to deteriorate further the environment. In this sense, farm management can influence greatly the environmental equilibrium of a territory. Therefore, the five variables used here, considered as proxies for agricultural intensification and farm marginalisation, include: crop intensity (INT), land rented for cultivation (AFF), farmer ageing (AGE), land abandonment (LOS), and an index of soil compaction risk (COM) due to heavy mechanisation. Crop intensity was estimated as the ratio of the intensively cultivated area (arable crop and orchards) on the total agricultural area (AUA, Agricultural Used Area) (Salvati et al., 2007). The land rented for cultivation was computed as the ratio of the rented agricultural surface to the AUA. Opposite to farmers who own their land, farmers renting it lack in long-time perspectives and prefer to arrange crop production with the aim of maximising the immediate profits (Ceccarelli et al., 2006). Farmer ageing was calculated as the ratio of agricultural workers which are more than fifty-five years old to the total number of agricultural workers. Young farmers show, on average, higher entrepreneurship and educational attainments, as well as a closer attention to the environmental matters than older farmers. Land abandonment was estimated by the rate of change in the cultivated land surface between 1990 and 2000 (Khanal and Watanabe, 2006). Finally, an index of soil compaction risk was calculated based on the density of agricultural machines available in each farm and classified by type and size according to data provided by the National Census of Agriculture (Salvati and Zitti, 2005). All variables were calculated at the municipal scale.

2.2.6. Climate

Climate is one of the most important determinants of LD (Sivakumar, 2007): low precipitations usually limit the vegetation cover and represent a constraint for crop growth. Moreover, extreme temperature values can adversely affect vegetation and the fertility of the soil by altering its physical properties. Generally speaking, climate exacerbation may worsen environmental conditions and this, assuming the other factors of pressure as constant, can easily lead to overexploitation of natural resources (e.g. increasing water demand/consumption for irrigation as a consequence of more severe and more frequent drought periods). Ten long-term (1971–2000) average variables quantifying precipitation and thermometric regimes, soil water balance, climate aridity, and drought severity were used here to describe the impact of climate on LD. These variables were calculated using basic information available in the National Agro-meteorological Database of the Italian Ministry of Agriculture. The database relates to meteorological data collected from about 3000 weather stations (e.g. Venezian Scarascia et al., 2006). To ensure the homogeneous and complete territorial coverage, the meteorological data were spatially interpolated through kriging and co-kriging procedures (with elevation, latitude, and distance to the sea as ancillary variables) in order to create a grid of 544 points covering the entire Italy with daily data of temperature, precipitation, humidity, solar radiation, and wind (Salvati et al., 2009).

Based on the considerations that values of annual precipitation under 300 mm are associated with significant loss of soil due to poor vegetation cover protecting from water/wind erosion, and that seasonal differences in precipitation regimes directly impact on water availabilities (Salvati et al., 2009), we described the precipitation regime by the following variables: the mean annual long-term precipitation (PRE), the average ratio of spring and summer precipitations (cumulated from April to September) to autumn and winter precipitations (cumulated from October to March) as a *proxy* of

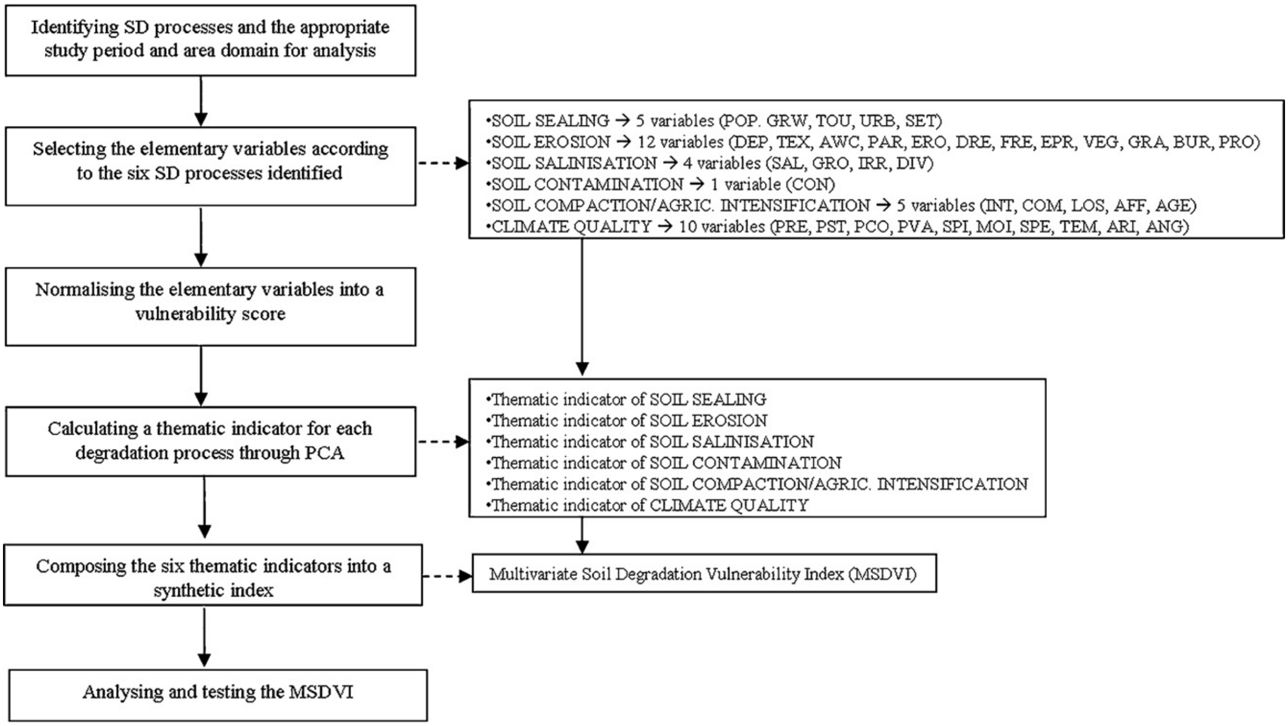

Fig. 1. Flowchart of the procedure steps to derive the Multivariate Soil Degradation Vulnerability Index (MSDVI).

rainfall seasonality (PST), and the average ratio of annual precipitations to the number of rainy days as a *proxy* of rainfall concentration (PCO). Finally, the coefficient of variation of the annual precipitation was computed to quantify the precipitation variability in terms of departures from the normal regime during the investigated period (PVA).

According to the Thornthwaite–Mather procedure (Thornthwaite, 1948; Mather, 1978), we estimated the monthly water balance of soil. It calculates reference evapotranspiration (Et_0), effective evapotranspiration, runoff, and average soil moisture (MOI). Et_0 was computed using the Penman–Monteith formula (Legates and McCabe, 2005; Incerti et al., 2007) from daily data of minimum and maximum temperature, solar radiation, wind speed, and relative humidity. Since the seasonal lack of water is the main factor limiting biological processes, to quantify climate aridity we used the standard aridity index (ARI) *sensu* UNEP (i.e. the ratio of mean annual precipitation to mean annual Et_0).

Long sequences of days without precipitation were considered here as a *proxy* for drought severity (Salvati et al., 2009b). Days with less than 1 mm precipitation were defined as ‘dry’ and a continuous period of at least 10 dry days was defined as a ‘dry period’ (SPE). The average annual number of dry days belonging to dry periods was computed accordingly. Moreover, the Standardized Precipitation Index (SPI) was introduced to quantify the abundance or deficit of rainfall. We thus calculated the mean annual frequency of SPI scores less than −0.99, which is the threshold indicating drought conditions (Heim, 2002). The average annual frequency of days with temperatures higher than 35 °C (TEM) was then calculated as a proxy for hot wave persistency.

Finally, according to the MEDALUS approach, the topographical relief was used as an additional *proxy* for climate quality. In fact, the slope exposure angle (ANG) influences sunshine intensity and duration thus affecting the soil microclimate; this can result, for example, in higher evapotranspiration rates on southern compared with northern exposures (Kosmas et al., 2003).

2.2.7. Statistical analysis

This study developed a specific approach based on the implementation of the model proposed by Salvati et al. (2009). In order to derive a synthetic index of land vulnerability to degradation they used a multidimensional analysis which proved to be effective to reduce data complexity, to remove redundancy among variables, and to estimate the importance of each considered variable. GIS tools were used to process the data to be submitted to the statistical analysis.

The procedure used in this paper consists of four steps: (i) variables normalisation; (ii) Principal Component Analysis (PCA) on the normalised data matrix; (iii) computation of the six thematic indicators as the weighted average of the elementary variables and, finally, (iv) computation of the synthetic index of land vulnerability to degradation as the weighted average of the six thematic indicators. A flowchart detailing the illustrated procedure is reported in Fig. 1. The procedure steps are detailed as follows.

All variables were converted to a regular spatial grid covering the entire Italy in order to achieve scale consistency among variables. The grid size was chosen according to variables' resolution. A 15 km random grid composed of 1346 nodes was created and the value of each variable was estimated at each grid node. All the variables were normalised as follows:

$$X_{y,i,j} = \frac{x'_{y,i,j} - x'_{y,\min,j}}{x'_{y,\max,j} - x'_{y,\min,j}} \quad (1)$$

$$X_{y,i,j} = 1 - \left[\frac{x'_{y,i,j} - x'_{y,\min,j}}{x'_{y,\max,j} - x'_{y,\min,j}}\right] \quad (2)$$

where $x'_{y,i,j}$ represents the observed value for the ith variable measured in the jth spatial unit in the yth year, and $x'_{y,\min,j}$ and $x'_{y,\max,j}$ respectively represent the minimum and maximum values for the ith variable measured at each node. Equation 1 was applied to the variables showing a positive relationship with LD, while Eq. (2) was applied to those showing a negative relationship with LD (Table 1).

Table 2
The weights assigned to each elementary variable by Principal Component Analysis (PCA).

Soil degradation process	Variable	Weight	Soil degradation process	Variable	Weight
Soil sealing	POP	0.935	Soil salinisation	SAL	0.444
	GRW	0.293		GRO	0.597
	SET	0.199		IRR	0.387
	URB	0.956		DIV	0.695
	TOU	0.205	Soil contamination	CON	1.000
Soil erosion	DEP	0.806	Soil compaction/agricultural intensification	INT	0.760
	TEX	0.554		AFF	0.298
	AWC	0.353		AGE	0.639
	PAR	0.676		LOS	0.301
	ERO	0.034		COM	0.722
	DRE	0.920	Climate quality	PRE	0.908
	FRE	0.323		PST	0.873
	EPR	0.857		PCO	0.885
	VEG	0.890		PVA	0.281
	GRA	0.107		SPI	0.275
	BUR	0.733		SPE	0.746
	PRO	0.352		TEM	0.326
				ARI	0.972
				MOI	0.985
				ANG	0.078

Each normalised variable ranges from 0 (the lowest contribution to land vulnerability) to 1 (the highest contribution to land vulnerability).

A Principal Component Analysis (PCA) was then applied to the matrix composed of all the normalised variables describing each degradation process. The number of significant axes (m) was chosen according to the components with absolute eigenvalues higher than 1. To assess the quality of the PCA outputs two tests were performed. The Kaiser–Meyer–Olkin measure of sampling adequacy tests whether the partial correlations among variables are small, while the Bartlett measure of sphericity tests whether the correlation matrix is an identity matrix. The structure of the data matrix was analysed by computing loadings, i.e. the correlation among the normalised variables and the selected PCA components. Following Salvati and Zitti (2008), a weight was attributed to each variable (Table 2) by multiplying its contribution (V_i) to the m PCA axes by their proportion of explained variance (C_k). The sum of these products for all the m axes corresponds to the weight (W_i) assigned to each variable:

$$W_i = \frac{\sum_{k=1}^{m}(V_i \cdot C_k)}{\sum_{j=1}^{n}\sum_{k=1}^{m}(V_i \cdot C_k)} \quad (3)$$

Weights were expressed as a value ranging between 0 and 1. Each of the six thematic indicators (I_t) was then obtained as the weighted average of the respective variables (Table 3):

$$I_t = \sum_{i=1}^{n}(W_i \cdot X'_{i,t}) \quad (4)$$

The same procedure (PCA and weighting assignment) was repeated in order to derive the MSDVI starting from the matrix composed of the six thematic indicators. The MSDVI was thus obtained as the weighted average of the six thematic indicators. MSDVI scores range between 0 and 1, respectively the lowest and the highest level of land vulnerability to degradation.

2.2.8. Validation

The ability of the MSDVI to discriminate different levels of land vulnerability to degradation was tested in three ways: (i) a qualitative comparison of the MSDVI map with existing vulnerability maps, (ii) a quantitative analysis of the relationship between the MSDVI and a standard measure of land sensitivity to degradation, and (iii) a field validation.

The qualitative validation was carried out by a visual comparison of the vulnerability maps produced in this and other studies, according to the list provided by Ceccarelli et al. (2006).

Concerning point (ii), the Environmentally Sensitive Area Index (ESAI) was chosen for comparison as it is considered as a LD sensitivity reference for the Mediterranean landscape (Brandt, 2005). The comparison was run at the same period, spatial resolution, and

Table 3
Average and coefficient of variation of the vulnerability scores estimated in Italy by soil degradation process and geographic belt.

LD process		North-west	North-East	Centre	South	Main islands
Surface area (km^2)		57,919	62,007	58,382	73,793	49,742
Soil sealing	Mean	0.053	0.041	0.037	0.042	0.038
	CV	1.30	0.95	1.16	1.08	0.98
Soil salinisation	Mean	0.008	0.060	0.070	0.100	0.130
	CV	5.33	3.17	2.43	2.10	1.54
Soil erosion	Mean	0.470	0.503	0.499	0.495	0.511
	CV	0.32	0.31	0.31	0.31	0.29
Soil pollution	Mean	0.014	0.021	0.039	0.011	0.016
	CV	3.88	2.02	3.77	1.80	1.51
Soil compaction	Mean	0.301	0.331	0.396	0.386	0.357
	CV	0.55	0.51	0.27	0.29	0.31
Climate quality	Mean	0.516	0.483	0.540	0.609	0.805
	CV	0.12	0.14	0.09	0.12	0.04

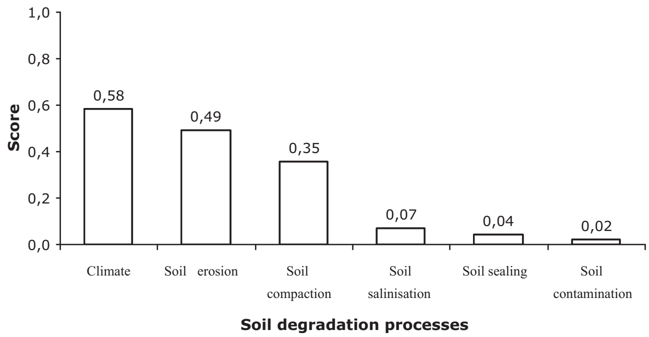

Fig. 2. Average score of the six thematic indicators in Italy.

geographical scale. The relationship between the MSDVI and the ESAI was assessed by a non-parametric Spearman rank correlation test.

Finally, a validation of the MSDVI (*sensu* Costantini et al., 2009) was carried out at 16 field sites, placed in both vulnerable and non vulnerable areas throughout Italy. Each site was geo-referenced and the possible causes of LD were briefly described within a 500 m circle plot centred on the coordinates of each point (Salvati et al., 2009). All field data were stored into a dedicated database organised as a check-list. The occurrence of twelve issues (climate, soil, and vegetation quality, crop intensity/soil compaction, population density and growth, urban sprawl and soil sealing, tourism pressure, fire risk, soil erosion, salinisation, and contamination risks, as well as habitat fragmentation) were estimated by way of a score ranging from 0 (absent) to 4 (high) following a visual assessment (Table 4). When necessary, additional information was obtained by interviewing experts involved in environmental planning and monitoring at both the regional and local scales (Ceccarelli et al., 2006). A number of pictures of the landscape and a recent aerial photograph of each site were added to the site information database. A final score was calculated as the average of the scores detected for each issue. It was then compared to the MSDVI calculated at the same site: the hypothesis is that the highest is the MSDVI, the highest is the score obtained in the field. The comparison was performed by means of Spearman rank correlation test.

3. Results

The average values of the six thematic indicators in Italy are illustrated in Fig. 2. The weights assigned to the elementary variables composing the indicators are reported in Table 2. In Italy, climate quality, soil erosion, and soil compaction/agricultural intensification were found as the processes with a potentially higher role in determining vulnerability to LD. However, they showed different spatial patterns as illustrated in Fig. 3. The land vulnerability to soil sealing was found relatively low throughout Italy. This process concentrated around cities, as well as in lowland and coastal areas. The variables contributing the most to this indicator are population density (POP) and proportion of built-up areas (URB). Land vulnerability to soil salinisation showed the opposite spatial pattern, increasing from northern to southern Italy, with the highest contribution provided by diversification of the irrigation sources used by the Italian farms (DIV) and percent surface area of farms practicing groundwater irrigation (GRO). The vulnerability scores attributed to the soil erosion process were found relatively high in the entire Italy, with the highest contributions provided by the drought resistance indicator (DRE), the rate of vegetation cover (VEG), vegetation protection against soil erosion (EPR) and soil properties include depth (DEP). The land vulnerability to soil contamination showed generally low scores with a clustered distribution associated to urban and industrial areas.

Table 4
LD and the related environmental pressures in Italy: field case studies (Fig. 8 reports site location; MSDVI scores were expressed as quartiles; see also Fig. 9 for some examples of *on-site* observations of LD processes).

Field site (Nuts-3 province)	Climate quality	Soil quality	Vegetation (land cover) quality	Crop intensity and soil compaction	Population density and growth	Urban sprawl and soil sealing	Tourism pressure	Fire risk	Erosion risk	Salinisation risk	Soil contamination risk	Habitat fragmentation	MSDVI score (2000)
1. Ferrara	**	****	**	***	***	***	**	*	*	***	**	***	**
2. Macerata	****	****	***	**	**	**	*	*	**	**	*	*	*
3. Grosseto	**	**	***	***	**	**	**	***	**	**	*	**	*
4. Viterbo	**	**	**	***	**	***	***	***	*	****	*	**	**
5. Rome	**	***	***	***	****	****	****	****	**	***	**	****	***
6. Campobasso	**	**	***	**	**	**	**	**	**	***	*	*	***
7. Bari	*	*	**	***	***	***	***	***	*	***	**	***	***
8. Matera	*	*	***	**	**	**	***	***	****	**	*	**	***
9. Taranto	*	*	**	***	***	***	***	***	*	***	**	***	***
10. Salerno	***	***	***	**	**	**	**	***	**	**	*	**	*
11. Cosenza	**	**	**	**	**	**	**	****	**	*	*	***	**
12. Catanzaro	**	**	**	**	**	***	***	****	*	***	*	***	***
13. Crotone	**	**	***	***	**	***	**	***	**	**	*	***	**
14. Nuoro	*	*	***	**	*	**	***	***	**	*	*	**	***
15. Cagliari	*	*	*	***	***	***	***	***	*	***	***	****	****
16. Ragusa	*	*	*	***	**	***	***	***	****	***	***	**	****

0: absent.
[*] Low.
[**] Moderately low.
[***] Moderately high.
[****] High.

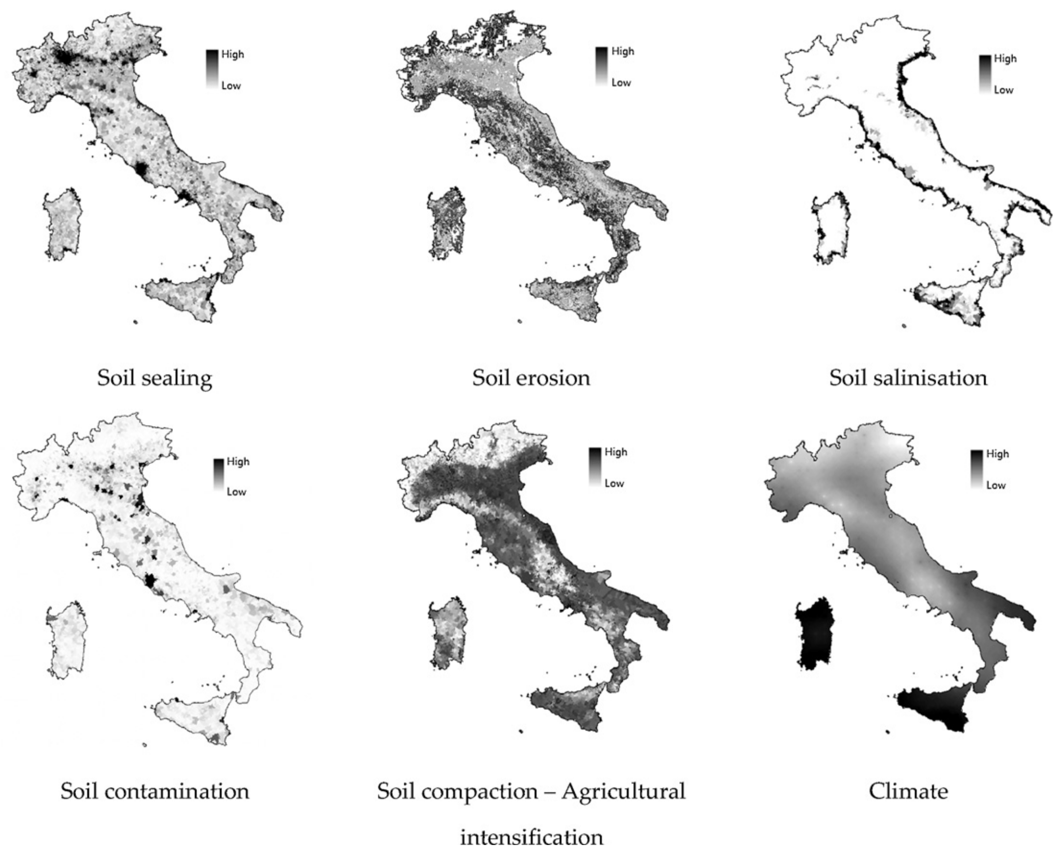

Fig. 3. Geographical distribution of the thematic indicators of vulnerability to each soil degradation process considered in this paper.

Finally, land vulnerability to soil compaction followed a latitude gradient from north to south, with the highest contributions provided by crop intensity (INT) and soil compaction risk index (COM). The same pattern was found for climate quality. The variables contributing the most to this indicator are average soil moisture (MOI), aridity index (ARI) and mean annual long-term precipitation (PRE).

The weights assigned to each thematic indicator for deriving the MSDVI are reported in Fig. 4. Weights range from 0.14 (soil salinisation) to 0.20 (soil compaction). The statistical distribution of the MSDVI was shaped asymmetrically (positive slope) with the average score and the coefficient of variation respectively amounting to 0.294 and 7.5%. The most vulnerable area was insular Italy, followed by southern Italy (Fig. 5). On average, northern and central Italy were found less vulnerable to LD. However, the MSDVI was found locally high also in northern Italy, especially in the region along the Po plain close to the Adriatic sea (Fig. 6).

The validation tests performed on MSDVI indicated that the index is a reliable *proxy* of land vulnerability to soil degradation. A visual comparison of the vulnerability maps produced in this and other studies (see list provided by Ceccarelli et al., 2006) pointed out the consistency of the different procedures aimed at monitoring LD. In all studies, areas prone to LD were found concentrated along the coasts of central and southern Italy, in some suburban regions, as well as in lowlands and neighbouring uplands especially in areas with dry climatic conditions, crop intensification, and growing population (large parts of Sicily, Sardinia, and Apulia, as well as restricted parts of Basilicata, Molise, Latium, Tuscany, and Emilia-Romagna).

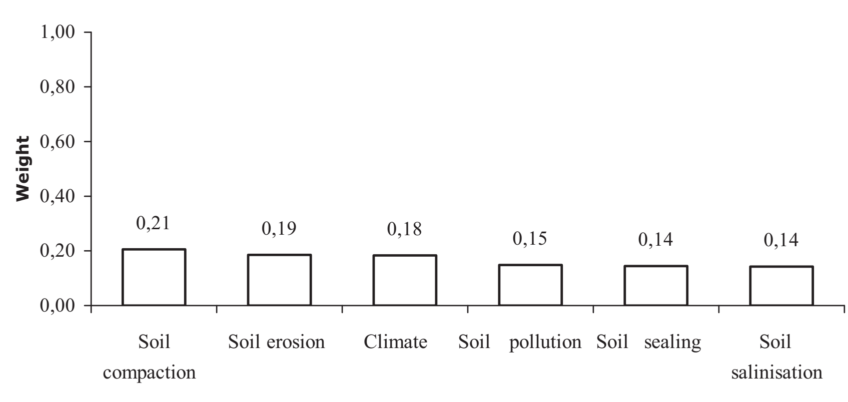

Fig. 4. Weight of the six thematic indicators composing the Multivariate Soil Degradation Vulnerability Index (MSDVI).

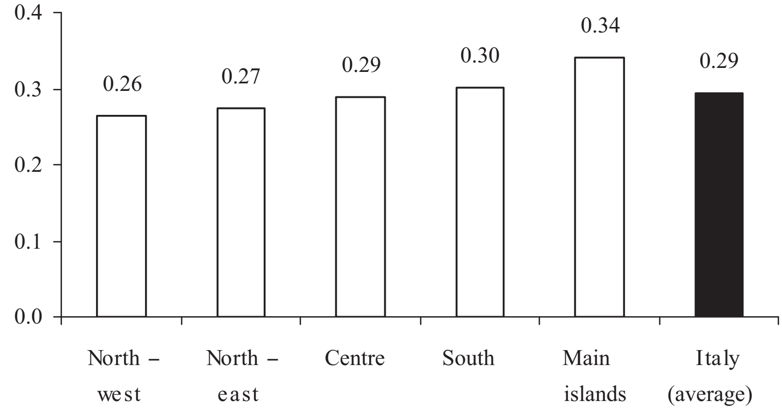

Fig. 5. Average score of the Multivariate Soil Degradation Vulnerability Index (MSDVI) in Italy by geographical belt.

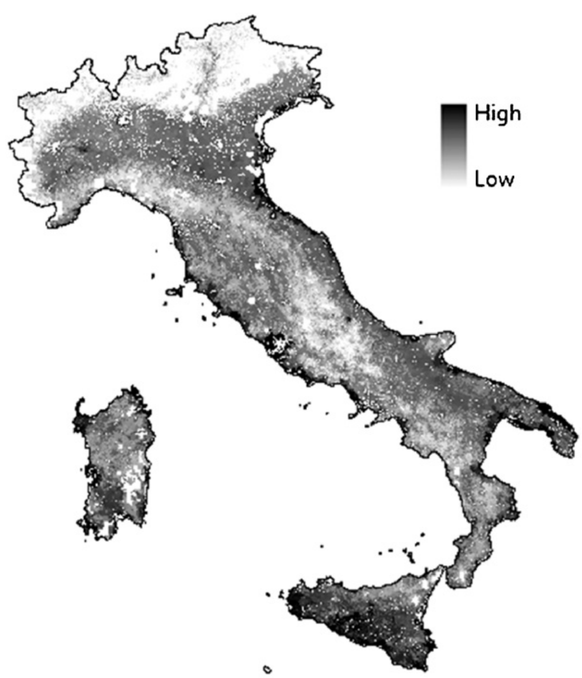

Fig. 6. The geographical distribution of the Multivariate Soil Degradation Vulnerability Index (MSDVI) in Italy.

A significant correlation between the MSDVI and the ESAI was observed ($R^2 = 0.554$, $p < 0.001$, $n = 1346$; Fig. 7). Although some differences between the two indexes could be found at the very local scale depending on site-specific factors (whose quantification is outside the scope of the present paper), the Spearman test results suggest that the MSDVI produces a reliable measure of LD vulnerability which is consistent to the ESAI.

Concerning field validation, Table 4 reports a synthesis of the information collected at the chosen sites (see also Fig. 8). On average, southern areas are characterized by a higher number of environmental problems related to LD than northern areas. Moreover, their severity is generally greater in southern Italy, and the MSDVI well reflects this condition: high MSDVI scores are associated with poor environmental conditions (Table 4). The final score of the visual assessment (Fig. 9) was found correlated to the corresponding score of the MSDVI ($R^2 = 0.835$, $p < 0.01$, $n = 16$). Finally, Fig. 10 illustrates some of the landscapes considered in Table 4 as a visual evaluation of their level of vulnerability to LD.

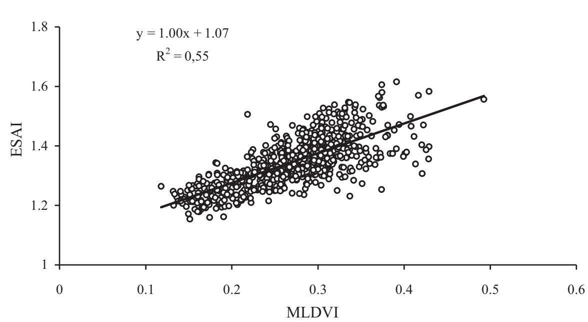

Fig. 7. The correlation between the Environmentally Sensitive Areas Index (ESAI) and the Multivariate Soil Degradation Vulnerability Index (MSDVI).

Fig. 8. The distribution of the validation plots in Italy.

Fig. 9. Some examples of *on-site* observations of LD processes (see also Table 2 for comparison with the MSDVI evaluation).

4. Discussion

A number of indexes of LD risk were developed within an early-warning framework (Basso et al., 2000; D'Angelo et al., 2000; Feoli et al., 2003). Such approach sometimes missed to quantify the importance of the specific soil degradation processes that contribute to (or directly determine) LD. This is not a criticism on indexes like the ESAI. In this view, the present paper does neither demise the importance of the early-warning assessment nor claim for a 'change in paradigm' in the analysis of LD. It rather calls for a more realistic 'coming back' to soil degradation processes as a honest guide in the estimation of the land vulnerability to degradation (Montanarella, 2007).

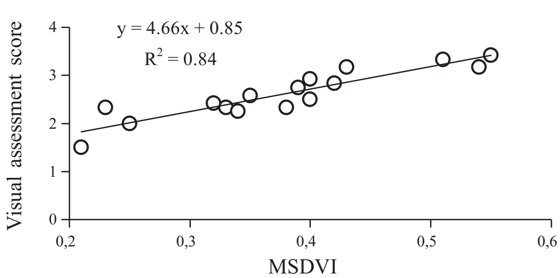

Fig. 10. Correlation between the Multivariate Soil Degradation Vulnerability Index (MSDVI) and the visual assessment score in each evaluation plot.

Improvements in this direction may strengthen the traditional approaches working along two research directions. One should be the implementation of a more effective early-warning assessment of the (potential) vulnerability to LD. The second direction involves the process-based estimation of the (actual) vulnerability to LD. Knowledge of the basic processes determining the level of the soil vulnerability of a certain area and assessing their interaction is crucial when effective policies against LD are to be undertaken (Lambin et al., 2001; Silleos et al., 2008).

In this perspective, this study has thus combined several indicators derived from both bio-physical and socio-economic data into a process-based evaluation of the land vulnerability (Huby et al., 2007). Tools based on GIS and multivariate statistics integrating bio-physical and socio-economic variables, like the one presented in this paper, are meaningful when setting up a DSS with the aim of devising strategies to mitigate the risk of desertification (Basso et al., 2000; D'Angelo et al., 2000; Feoli et al., 2003; Diodato and Ceccarelli, 2004). As a synthetic index of LD vulnerability aggregating six indicators of land vulnerability to specific soil degradation processes, the MSDVI can be regarded as a tool suited to implement mitigation strategies at both the national and the regional level (Hill et al., 2008). The procedure was designed to provide results at a multi-resolution spatial scale covering relatively large areas (national level) and relying on detailed information layers (local/regional level). This up- and down-scaling approach allows, for instance, to compare different local evidences each other, to extend information from a local to a national perspective, to charac-

Table 5
Examples of 'soft' indicators by soil degradation process and theme partition.

Soil degradation process	Theme partition	Variable
Soil sealing	Urbanization	% municipalities with sustainable planning
Soil erosion	Soil properties	Stoniness
		Soil drainage
		Organic carbon soil content
	Land cover and management	Replacement costs of wood fires
		Agro-environmental farms (e.g. EU reg. 2078)
Soil salinisation	Secondary salinisation	Surface area prone to secondary salinisation risk
Soil contamination	Mining	Mining activities
Soil compaction/agriculture	Agricultural land use	% agricultural utilised area
		% agricultural total area
		Crop diversification index (Shannon)
		Irrigated agricultural areas
		Irrigable agricultural areas
		Irrigated farm surface area/total farm surface
		Irrigatable farm surface area/total farm surface
		Land profitability index
	Farm management	% family farms
		% full-time farmers
		% employed in the primary sector
		% economically marginalised farms (<2 ha)
		% organic farming surface
		Tourism rural hospitality
Cimate quality	Precipitation	Runoff
		Water deficit
	Temperature	Growing degree day ($T > 15\,^{\circ}$C)
		Et_0
		Et_R
		Slope

terize the national territory in (regional) homogeneous units of land vulnerability to soil degradation and analyse them diachronically.

The MSDVI, tested for robustness by using different datasets, showed a spatial distribution similar to the ESAI with the advantage of considering a potentially larger number of themes and related variables. The risk of redundancy when manipulating a high number of variables was minimised using a multivariate analysis such as the Principal Component Analysis (Salvati and Zitti, 2008). Notably, the elementary variables, the statistical procedures to aggregate them into thematic indicators, and the composition of the indicators to produce the MSDVI could be changed without affecting the validity of the proposed methodology, but adapting it to applications in another environmental conditions well outside the Mediterranean region for which it was originally implemented.

5. Conclusions

The results of this study indicate that the most critical areas in Italy are those located along the coastal lowlands where population and economic activities are mostly concentrated. Interestingly enough, a high degree of vulnerability is also observed in some internal areas of southern Italy with unfavourable climatic conditions and geo-morphological features ultimately leading to LD (e.g. land gullies, poor land cover, steep slope). These conditions are often associated to the unsustainable exploitation of the agricultural lands (Salvati et al., 2007).

Despite the validation efforts described in this paper, there is certainly scope for improving the indicators system and the applied statistical and GIS procedures. One critical point is the choice of the variables to be considered in the empirical framework. In general, an objective choice (e.g. based on a statistical methodology) is not to be preferred to a subjective choice, since the latter could better illustrate, although not backed by quantitative assessments, the complexity of certain causal relationships. A reasonable compromise could be to have, at least in a first step, a wide range of indicators selected on subjective grounds (e.g. weights given by different experts, different geographic contexts and underlying determinants). This can be followed by a second step of the analysis centred on a statistical analysis allowing the objective selection of a restricted set of indicators (Brandt, 2005). This is the approach followed in the present paper.

The use of indicators at two levels, which are referred here as respectively (i) 'hard indicators' and (ii) 'soft indicators', could contribute to a mixed selection strategy. We define hard indicators as those showing a relatively well documented relationship with LD. On the contrary, soft indicators depict less proven cause–effect relations and show only an indirect link with LD. 'Soft indicators' should not be included in formalised assessment models, but are still useful when describing the environmental conditions of vulnerable lands. This work is an example of the approach. 'Hard' indicators are those used in the multivariate analysis and contributing to the MSDVI. Additional 'soft' indicators can be used in a narrative interpretation of degradation processes and affected areas. An example of possible 'soft' indicators which are related to each degradation process considered here is given in Table 5.

Finally, we are convinced that a comprehensive framework is urgent to devise an exhaustive and periodic monitoring of LD. It should be based on the integration of country and regional studies (which in turn are based on composite indices of land vulnerability and remote-sensing information, Feoli et al., 2003) with local-level studies (based e.g. on social enquiries, Wilson and Juntti, 2005) and *on-site* validation of general model outputs (Kok et al., 2004). In this framework, the procedure presented here is not alternative to the standard ESAI approach. Instead it could provide ancillary information to be used side by side with standard indexes with the aim of precisely estimate the role of several different degradation processes assumed to be influencing the vulnerability of a certain area.

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