Methodological appendix

Construction of the index of desertification risk

The ESA methodology

The Environmentally Sensitive Area (ESA) approach was launched in 1987 in the UK by the Ministry of Agriculture, Fisheries and Food (now the Department for Environment, Food and Rural Affairs) to encourage farmers and landowners to adopt environmentally-friendly land management practices (Wilson, 1996). In the early 1990s, the ESA framework was adapted to monitor desertification processes on the behalf of the MEDALUS project (Kosmas *et al.*, 1999). Although possible drawbacks of this framework have been discussed by Basso *et al.* (2000, 2012) and Bajocco *et al.* (2011), the ESA scheme remains one of the most well-used procedures to evaluate the sensitivity of land to desertification (e.g. Kosmas *et al.*, 1999; Bakra *et al.*, 2012; Mohammed, 2012). The main advantages of the ESA are flexibility in the use of the input variables and the simplicity of the land classification based on its level of sensitivity. The outcomes of the ESA model have been extensively validated on the ground at several sites in southern Europe (Kosmas *et al.*, 1999; Basso *et al.*, 2000; Bajocco *et al.*, 2011) and a regional assessment (Lavado Contador *et al.*, 2009) based on heterogeneous geographical datasets with different reliability, indicates the ESAI as a proxy for land degradation processes and identifies significant correlations with a number of indicators of soil degradation. Finally, Ferrara *et al.* (2012) evaluated the stability of the ESAI using statistical analysis and the sensitivity to changes in the indicators. Results indicate that the ESAI is a stable and reliable index not significantly affected by spatial and temporal heterogeneity in the composing indicators.

Despite its acknowledged importance as a tool to detect desertification risk, the ESA approach presents some shortcomings (e.g. Salvati *et al.*, 2013). The methodology does not provide an assessment of the importance of the individual variables or thematic indicators. In addition, the input variables are oriented towards the description of the bio-physical conditions of the area, while a number of socio-political and cultural factors considered as important in influencing the processes of land degradation, is not explicitly formalized through the use of appropriate quantitative variables (Salvati & Bajocco, 2011). According to the ESA framework the variables selected to study the level of land sensitivity to desertification in Italy refer to three themes: climate quality, soil quality, vegetation/land-use quality. In our experience, the layers used are the most reliable, updated and referenced data currently available to be used in the regional and country assessment of the ESAI in Mediterranean countries (see also Salvati, 2012 for a discussion on supply-demand of statistical data in desertification matters).

Environmental variables and thematic indicators

Climate quality has been described in the present study using the following variables: average annual rainfall rate, aridity index, and aspect (Basso *et al.*, 2000). Rainfall rate and the aridity index were calculated on a ten-year base using information collected in the Agro-meteorological Database of the Italian Ministry of Agriculture. The database relates to gauging data collected daily from various meteorological and hydrological networks (Italian Ministry of Agriculture, National Hydrological Service, Italian Air Force, and some minor networks) operating with nearly 3,000 weather stations since 1951. The aridity index was defined as the ratio between rainfall and reference evapotranspiration measured as a ten-year average. The reference evapotranspiration rate was calculated by using the Penman-Monteith formula (Salvati and Bajocco, 2011). Aspect was derived from elaboration on the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) global Digital Elevation Model (DEM) at 30m resolution scale generated from stereoscopic pairs of optical ASTER images and freely available online at http://www.gdem.aster.ersdac.or.jp/. Meteorological data were interpolated through geo-statistical procedures (using elevation, latitude, and distance to the sea as ancillary variables) to ensure the homogeneous national coverage. A grid composed by 544 points with daily data of temperature, precipitation, humidity, solar radiation, and wind has been created.

Soil data derived from the European Soil Database at a 1 km^2 pixel resolution (Joint Research Centre, JRC). The following sources of data also provided ancillary information: (i) an Italian database of soil characteristics ('Map of the water capacity in agricultural soils') generated by the Ministry of Agriculture and based on nearly 18,000 soil samples (Salvati, 2012); (ii) thematic cartographies including Ecopedological and Geological maps of Italy, obtained from the Joint Research Centre and the Italian Geological Service) and, finally, (iii) a land system map produced by the National Centre of Pedological Cartography. These datasets can be considered as the standard, homogeneous soil information available in Italy at 1:250,000 scale. The variables considered in this study include soil depth and texture, slope, and the nature of the parent material. These variables can be considered as proxy information for other soil quality indicators (e.g. organic matter content, resistance or tendency to compaction). Soil structural characteristics including texture, depth, and parent material are determined by the joint action of factors including climate, soil organisms, morphology, and time (Kosmas *et al.*, 1999). In our case study, considering the examined time span, these variables have been regarded as static during the study period because they change slowly, if at all or, by their nature, are infrequently measured (Bajocco *et al.*, 2011). The long investigated time period and the national coverage of the study prevented us from using diachronic soil mapping available at the very local scale. However, it should be noted that, among the considered variables, soil depth can vary along prolonged time intervals and in places with specific territorial characteristics possibly due to the effect of soil erosion.

The importance of vegetation cover in land degradation processes was evaluated through four variables: vegetation cover, fire risk, protection offered by vegetation against soil erosion, and the degree of resistance to drought shown by vegetation (Basso *et al.*, 2000). Such variables derived from elaboration on CORINE land cover maps. Variables were determined by applying a weighting system (ranging from 1 to 2 and derived from Kosmas *et al.*, 2000) that classifies each observed land cover class according to the level of sensitivity to land degradation. The CLC program was developed by the European Environment Agency (EEA) using satellite imagery to provide pan-European, diachronic 1:100.000 land cover maps with 25 ha minimum mapping unit. The CLC nomenclature includes 44 land cover classes grouped into a three-level hierarchy. Although the data material used in the present study has obvious shortcomings, this may be acceptable when the purpose is to study a large region (e.g. a whole country) over a long time interval, since the cost of mapping is insurmountable for an individual research project. It is therefore inevitable that such large scale studies rely on sources of varying accuracy.

The composite index of land sensitivity to degradation

The ESAI framework quantifies sensitivity to land sensitivity as a combination of unsustainable land management together with environmental factors including poor soil, vegetation cover and dry (or drier) climate (Basso et al., 2000; Lavado Contador *et al.*, 2009). A scoring system is applied, based on the known relationship between each factors and land degradation processes. The weighting system suggested by Salvati and Bajocco (2011) was adopted in the present study. This system followed the benchmarking system introduced by

Kosmas *et al.* (1999), Basso *et al.* (2000), and Lavado Contador *et al.* (2009). The ESA framework produces quality indicators of climate (Climate Quality Index, CQI), soil (Soil Quality Index, SQI), and vegetation (Vegetation Quality Index, VQI), that are estimated as the geometric mean of the different scores assigned to each input variable. Each indicator ranges from 1 (the lowest contribution to land sensitivity to degradation) to 2 (the highest contribution to land sensitivity to degradation). The ESAI was then estimated in each spatial unit and year as the geometric mean of the four quality indicators (CQI, SQI, VQI) obtaining a score ranging from 1 (the lowest sensitivity to degradation) to 2 (the highest sensitivity to degradation). The four indicators weighted the same in the ESAI procedure (Kosmas *et al.*, 1999). Four classes of land sensitivity were identified that reflect the classification threshold shown in Salvati and Bajocco (2011): (i) areas unaffected by LD (ESAI < 1.17), (ii) areas potentially affected by LD (1.17 < ESAI < 1.225), (iii) 'fragile' areas (1.225 < ESAI < 1.375), and (iv) 'critical' areas (ESAI > 1.375). Maps have been produced at 1 km^2 pixel resolution (Salvati, 2012). The elementary spatial unit has been selected according to Basso *et al.* (2000) and is coherent with the resolution of the single layers.

Construction of the index of Sustainable Development

Sustainability indicators

The variables used in the present study have been made available at the municipal scale (8100 administrative units in Italy) from data provided by official statistical sources (mainly obtained from censuses carried out by the Italian National Statistical Institute [Istat]. A total of 99 indicators has been calculated from the collected variables for each municipality and classified into six main themes and 14 research dimensions (Table 1). The selection of variables, the procedure for the construction of indicators, and the identification of the thematic dimensions adequate to describe the socioeconomic and territorial context possibly influencing the level of sustainable development at the local scale have been set up according to the indications provided in Ronchi et al. (2002). Although the indicators selected in the present study cannot be considered as an exhaustive description of the varying socioeconomic contexts of Italy, they provide a broad qualification of the economic structure, social traits, and environmental characteristics observed in the Italian municipalities. All selected indicators are freely available from national statistical sources and regularly updated through time, allowing for full replicability of the illustrated approach (Table 2).

Building-up the composite index of sustainable development

As reported in Figure 1, the procedure implemented to build up the composite index of sustainable development consists of seven steps including variables' selection, data transformation, multivariate statistical analysis, weight derivation, indicators' composition and descriptive statistics of the obtained index. According to OECD (2008) data transformation was carried out according to four hypotheses while variables' weighting and indicators' composition were carried out respectively based on two hypotheses, for a total of eight composition models. Data normalization has been carried out according to the following formula:

$$X_{t,i,j} = (x'_{t,i,j} - \text{average}(x))/(\text{standard deviation}(x)) \quad (1)$$

Data standardization was carried out according to the following formulas:

$$X_{t,i,j} = (x'_{t,i,j} - x'_{t,\min,j})/(x'_{t,\max,j} - x'_{t,\min,j}) \quad (2)$$

$$X_{t,i,j} = 1 - [(x'_{t,i,j} - x'_{t,\min,j})/(x'_{t,\max,j} - x'_{t,\min,j})] \quad (3)$$

where $x'_{t,i,j}$ represents the observed value for the variable *i* measured over the spatial unit *j* in the year *t*, $x'_{t,min,j}$ and $x'_{t,max,j}$ respectively are the minimum and maximum values for the variable *i* measured in all the spatial units. Eq. (2) was applied to variables with a positive relationship with local sustainability while Eq. (3) was applied to variables which showed a negative association to local sustainability, as reported in Table 2. Each standardized variable ranges from 0 (the highest contribution to local sustainability) to 1 (the lowest contribution to local sustainability).

A Principal Components Analysis (PCA) was undertaken on the data matrix described in paragraph 2.2 (99 variables • 8100 municipalities) in order to summarize the latent factors describing the varying socioeconomic and environmental contexts in Italy. As the PCA was based on the correlation matrix, the number of significant axes (*m*) was chosen by retaining the components with eigenvalue > 3. The Keiser-Meyer-Olkin (KMO) measure of sampling adequacy, which tests whether the partial correlations among variables are small, and Bartlett's test of sphericity, which tests whether the correlation matrix is an identity matrix, have been used in order to assess the quality of PCA outputs. Variables' weights based on the PCA were attributed by multiplying the contribution of each variable (V_i) to the *m* most important factorial axes of the PCA (Coppi and Bolasco, 1989) selected as described above with their proportion of explained variance (C_k). The sum of these products for all the *m* selected axes represents the weight (W_i) attributed to each variable:

$$W_i = \frac{\sum_{k=1}^{m} (V_i \cdot C_k)}{\sum_{j=1}^{n} \sum_{k=1}^{m} (V_i \cdot C_k)} \quad (4)$$

Weights are expressed in percentages and range between 0 and 1. After PCA and variables' weighting, composite indexes were calculated according to the eight models described above (a combination of different data transformation methods, variables' weighting and indicators' composition techniques). The most stable index was selected comparing the different models by descriptive and non-parametric correlation analyses based on Spearman co-graduation rank tests. The index derived from the most stable model was identified as the Composite Index of Sustainable Development (CISD) at the local scale in Italy. Descriptive statistics of the CISD have been calculated using the three main geographical divisions in Italy (northern, central, and southern Italy). Maps have been created with the aim at illustrating the ranking of each Italian municipality based on the CISD.

Validation

The ability of the composite index to discriminate among different levels of sustainable development in the Italian municipalities was tested by correlating CISD scores to three independent variables at vastly different spatial scales, ranging from the local municipality (the same scale used to develop the CISD) to the prefecture and the administrative regions of Italy: (i) per-capita value added provided by CENSIS (2004) at the municipal scale (n = 8100 units), (ii) the indicator of sustainable development and quality of life calculated yearly by an Italian economic newspaper (Sole24Ore) at the provincial level (n = 103 units) and based on quantitative indicators elaborated through statistical techniques and (iii) the QUARS index developed by Lunaria (2004) at the regional scale (n =

20 units) using environmental, economic and social indicators from official statistics. According to data availability, comparisons were run at the same period using linear correlations (Pearson coefficient) and non-parametric co-graduation tests (Spearman ranks).

SM.Table 1. A scheme illustrating the number of indicators selected by theme and research dimension.

Themes	Research dimensions	Indictors
Demography	Population structure (P)	6
	Territorial characteristics and urban structure (U)	13
Environment (E)	Water management	6
Human capital	Education (F)	5
	Labour market (L)	12
Local development and competitiveness	Economic structure (S)	6
	Tourism specialization (T)	5
Quality of life	Income and wealth (W)	13
	Crime (D)	4
Rural development (A)	Land tenure	5
	Rural landscape	11
	Crop intensity	6
	Quality and innovation in agriculture	5
	Human capital in agriculture	4

SM.Table 2. The list of indicators used in the present study.

Acronym	Variable	Dimension	Source	Sign	Year
E1	Per capita distributed water	Environment	ISTAT	-	1999
E2	Water dispersion index	Environment	ISTAT	-	1999
E3	Consumed water/inhabitants	Environment	ISTAT	-	1999
E4	Water tanks/inhabitants	Environment	ISTAT	+	1999
E5	Reservoir capacity/100 inhabitants	Environment	ISTAT	+	1999
D1	Crime intensity index	Crime	ISTAT	-	2002
D2	Crime severity index	Crime	ISTAT	-	2002
D3	Number of crimes per 1000 inhabitants	Crime	ISTAT	-	2002
D4	Work accidents per 100 inhabitants	Crime	INAIL	-	2002
U1	Compact urban settlements on total urban area (%)	Urban structure	EEA	+	2000
U2	Dispersed urban settlements on total urban area (%)	Urban structure	EEA	-	2000
U3	Mining areas (%)	Urban structure	EEA	-	2000
U4	Landfill areas (%)	Urban structure	EEA	-	2000
U5	Urban parks (%)	Urban structure	EEA	+	2000
U6	Leisure and sport areas (%)	Urban structure	EEA	+	2000
U7	Agricultural land	Urban structure	EEA	+	2000
U8	Population density (inhabitants / km^2)	Urban structure	EEA	-	2000
U9	Total population change (%)	Urban structure	ISTAT	+	2001
U10	Urban population (%)	Urban structure	ISTAT	+	2001
U11	Ecological footprint per km^2	Urban structure	ISTAT	-	2001
U12	Non-occupied dwellings (%)	Urban structure	ISTAT	-	2001
U13	Average dwelling size per inhabitant (m^2)	Urban structure	ISTAT	-	2001
F1	Population with tertiary-level education (%)	Education	ISTAT	+	2001
F2	Population graduated in high-school (%)	Education	ISTAT	+	2001
F3	Population with secondary education (%)	Education	ISTAT	+	2001
F4	Population with primary education (%)	Education	ISTAT	-	2001
F5	Illiterate population (%)	Education	ISTAT	-	2001
L1	Participation rate	Labour market	ISTAT	+	2001
L2	Female workers to total workers (%)	Labour market	ISTAT	+	2001
L3	Consultants to total workers (%)	Labour market	ISTAT	+	2001
L4	Temporary workers on total workers (%)	Labour market	ISTAT	-	2001
L5	Voluntaries to total workers (%)	Labour market	ISTAT	-	2001
L6	Employment rate	Labour market	ISTAT	+	2001
L7	Unemployment rate	Labour market	ISTAT	-	2001
L8	Unemployment rate of age group 15-34	Labour market	ISTAT	-	2001
L9	Female participation rate	Labour market	ISTAT	+	2001
L10	Female employment rate	Labour market	ISTAT	+	2001
L11	Female unemployment rate	Labour market	ISTAT	-	2001
L12	Female unemployment rate of age group 15-34	Labour market	ISTAT	-	2001
P1	Average household size	Population structure	ISTAT	+	2001
P2	Population aged 80 ys and over on children 0-5 ys (%)	Population structure	ISTAT	-	2001
P3	Proportion of population aged 75 years and over	Population structure	ISTAT	-	2001
P4	Elderly index	Population structure	ISTAT	-	2001
P5	Dependency ratio	Population structure	ISTAT	-	2001
P6	Resident foreign people per 100 inhabitants	Population structure	ISTAT	+	2001
Q1	Subscriptions to state television channels (%)	Income and wealth	ISTAT	+	2001
Q2	Per capita municipal solid waste tax amount (euros)	Income and wealth	RAI	+	2002
Q3	Per capita disposable income (euros)	Income and wealth	ISPRA	+	2002
Q4	Per capita consumption	Income and wealth	TAGLIACARNE	+	2002

Table 2. (continued)

Acronym	Variable	Dimension	Source	Sign	Year
Q5	Per capita GDP	Income and wealth	CENSIS	+	2003
Q6	Amount of bank deposits by branch (euros)	Income and wealth	TAGLIACARNE	+	2002
Q7	Amount of bank deposits by inhabitant (euros)	Income and wealth	TAGLIACARNE	+	2002
Q8	Amount of bank loans by branch (euros)	Income and wealth	TAGLIACARNE	+	2002
Q9	Bank loans/deposits	Income and wealth	TAGLIACARNE	+	2002
Q10	Amount of bank loans by inhabitant (euros)	Income and wealth	TAGLIACARNE	+	2002
Q11	Per capita income tax amount (euros)	Income and wealth	TAGLIACARNE	+	2002
Q12	Per capita real estate tax amount (euros)	Income and wealth	TAGLIACARNE	+	2002
S1	Average number of workers per industrial local unit	Economic structure	TAGLIACARNE	+	2002
S2	Workers in hotel and restaurant services (%)	Economic structure	ISTAT	+	2001
S3	Density of workers by km^2	Economic structure	ISTAT	+	2001
S4	Working in manufacturing industry (%)	Economic structure	ISTAT	+	2001
S5	Working in agriculture, hunting and fishing (%)	Economic structure	ISTAT	+	2001
S6	Working in transport and communication services (%)	Economic structure	ISTAT	+	2001
A1	Indication of origin vineyards on total UAA(%)	Rural development	ISTAT	+	2001
A2	Rented Utilized Agricultural Area on total UAA (%)	Rural development	ISTAT	+	2000
A3	State-owned UAA on total UAA (%)	Rural development	ISTAT	-	2000
A4	Average farm size (hectares)	Rural development	ISTAT	+	2000
A5	Total agricultural land / total municipal area (%)	Rural development	ISTAT	+	2000
A6	UAA / Total agricultural land (%)	Rural development	ISTAT	+	2000
A7	Employees in the primary sector (%)	Rural development	ISTAT	+	2000
A8	Farmholders > 55 years (%)	Rural development	ISTAT	+	2000
A9	Farmholders on total workers in agriculture (%)	Rural development	ISTAT	-	2000
A10	Farmholders with technical education (%)	Rural development	ISTAT	+	2000
A11	Farmholder's activity diversification index	Rural development	ISTAT	+	2000
A12	Number of machines per UAA	Rural development	ISTAT	-	2000
A13	Irrigated land / total UAA (%)	Rural development	ISTAT	-	2000
A14	Number of hectares of UAA per worker	Rural development	ISTAT	+	2000
A15	Crop intensity index	Rural development	ISTAT	-	2000
A16	UAA under environmental protection (%)	Rural development	ISTAT	+	2000
A17	Arable land / Agricultural utilized area (%)	Rural development	ISTAT	+	2000
A18	Perennial crop / Agricultural utilized area (%)	Rural development	ISTAT	+	2000
A19	Pastures and meadows / Agricultural utilized area (%)	Rural development	ISTAT	+	2000
A20	Diversity in farm size (Shannon index)	Rural development	ISTAT	+	2000
A21	% woodland surface area in total farm surface	Rural development	ISTAT	+	2000
A22	% change in agricultural utilized area (1990-2000)	Rural development	ISTAT	+	2000
A23	Agricultural landscape diversity (Shannon index)	Rural development	ISTAT	+	2000
A24	Agricultural utilized area under organic farming (%)	Rural development	ISTAT	+	2000
A25	Livestock organic farms / Total farms (%)	Rural development	ISTAT	+	2000
A26	UAA under good agronomic practices (%)	Rural development	ISTAT	+	2000
A27	UAA under sustainability certification (%)	Rural development	ISTAT	+	2000
A28	Number of cattle / UAA	Rural development	ISTAT	-	2000
A29	UAA applying sustainable irrigation (%)	Rural development	ISTAT	+	2000
A30	Index of economic marginalization of farms	Rural development	ISTAT	-	2000
A31	Woodlands and semi-natural area (%)	Rural development	EEA	+	2000
T1	No. beds in hotels and campings / resident population	Tourism	ISTAT	+	2001
T2	Average number of beds per hotel	Tourism	ISTAT	+	2001
T3	Hotel occupancy level (five-years average)	Tourism	ISTAT	+	2001
T4	Rural hospitality occupancy level (five-years average)	Tourism	ISTAT	+	2001
T5	No. beds in agri-tourism accomodation / beds in hotel	Tourism	ISTAT	+	2001

SM.Figure 1. Schematic representation of the procedure developed in the present study to build up the indicator system measuring sustainable development in Italy.