TITLE: MONITORING SENSITIVITY TO LAND DEGRADATION AND DESERTIFICATION WITH THE ESAI METHODOLOGY: THE CASE OF LESVOS ISLAND

SHORT TITLE: MONITORING SENSITIVITY TO LAND DEGRADATION AND DESERTIFICATION

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ABSTRACT

In Europe, the most susceptible areas to land degradation and desertification (LDD) are found in the Mediterranean region. The present study focuses on the island of Lesvos (Greece) and maps the environmental sensitivity of the island to LDD between the years 1990 and 2000. Sensitivity is estimated with a modification of the MEDALUS Environmentally Sensitive Area Index (ESAI) approach, employing 21 quantitative parameters divided in five main quality indices: climate, vegetation, soils, groundwater and socio-economic quality. Parameterisation of these indices is achieved via remote sensing and ancillary data in a GIS. Results show that ~85% of the island is fragile or critically sensitive in both epochs. Fragile areas are on the increase, covering an estimated 72% of the island in 1990 and 77% in 2000, while critically sensitive areas decrease from 214km^2 to 113km^2. By modifying the ESAI to include 10 additional parameters related to soil erosion, groundwater quality, demographic as well as grazing pressure, and by applying the modified ESAI in two -rather than one- periods this study was able to identify that, contrary to previous belief, critically sensitive areas are also found in the eastern side of the island mainly due to human-related factors. It is concluded that the proposed methodology is a useful tool for regional scale trend analyses of environmental sensitivity and the identification of LDD hot-spots in Mediterranean environments.

Keywords: Land degradation, Desertification, MEDALUS, Environmentally Sensitive Area, Mediterranean, Remote sensing, GIS

INTRODUCTION

Land degradation, i.e. the ‘reduction or loss in the biological or economic productive capacity of the land caused by human activities, exacerbated by natural processes, and often magnified by the impacts of climate change and biodiversity loss’ (UNCCD, 1994), takes place in all agro-ecological zones threatening some 1.5 billion people (Nachtergaele *et al.*, 2010).

Desertification, a specific kind of land degradation, occurs mainly, but not exclusively, in dryland regions (Baartman *et al.*, 2008) and is affecting some 1.9 billion hectares of land word-wide and 250 million people (UNCCD, 2004; Low, 2013). The various definitions of, and perspectives on, desertification will not be repeated here but their sheer existence is indicative of the fact that it is still difficult to identify a unifying explanation of the causes of desertification (e.g. Lambin *et al.*, 2001; Reynolds & Stafford Smith, 2002; Geist & Lambin, 2004; Geist, 2005; Reynolds *et al.*, 2007).

In the Mediterranean region, desertification as an outcome of climatic and social driving forces operating in tandem is not a recent phenomenon (Conacher *et al.*, 1998; Puigdefábregas & Mendizabal, 1998). According to the UNCCD (2004), the countries of Portugal, Spain, Italy, Greece and Turkey have a marked problem of desertification because of the occurrence of particular conditions over large areas. International and interdisciplinary research initiatives have come to support this statement and have provided ample documentation that over the last decades large areas of the European Mediterranean region are being increasingly affected by desertification (Drake & Vafeidis, 2004; Kepner *et al.*, 2006; Sommer *et al.*, 2011).

Unfortunately, the breadth, complexity and dynamism of the desertification process has so far precluded the development of a comprehensive model and methods of assessment and monitoring have involved the use of indicators (Kosmas *et al.*, 1999a; Brandt *et al.*, 2003). Geeson (2005), Baartman *et al*. (2007) and Sommer *et al.* (2011) give thorough reviews of such indicator systems which usually describe one or more aspects of desertification and provide data on threshold levels, status and evolution of relevant physical, chemical, biological, and anthropogenic processes. The most frequently applied indicator-based system for assessing land degradation and desertification (LDD) in the Mediterranean region is the Environmentally Sensitive Area (ESA) framework, mainly due to its simplicity in model building as well as its flexibility in the use of relevant variables as indicators (Kosmas *et al.*, 1999a; Salvati *et al.*, 2011). In this system, the four main LDD factors of climate, soil, vegetation and land management are combined in a synthetic way to produce the so called ESA Index or ESAI (Kosmas *et al.*, 1999a). Kosmas *et al.* (1999b) used a set of indicators to map environmental sensitivity to desertification occurring in the island of Lesvos (Greece), one of the experimental test sites for examining desertification processes under the MEDALUS project. Other similar applications, in the Mediterranean region and elsewhere, include the work of Basso *et al.* (2000) who worked at another MEDALUS task area, the Agri basin in Sardinia; Coscarelli *et al.* (2005) in Calabria, Italy; Sepehr *et al.* (2007) in the Fidoye-Garmosht area in southern Iran; Lavado Contador *et al.* (2009) in the Spanish Province of Extremadura; Ladisa *et al.* (2012) in the Apulia region of southeast Italy; Izzo *et al.* (2013) who modified the ESAI to apply it in the Dominican Republic and Jafari and Bakhshandehmehr (2013) who combined fuzzy logic and the ESAI to map environmental sensitivity in central Iran.

All of the abovementioned studies estimate environmental sensitivity in one time step, i.e. they give emphasis on a static system. However, LDD processes, in essence, are dynamic since they operate in the time dimension (Hill *et al.*, 2008). LDD indicators should, therefore, be derived from a sequence of temporal steps so that their dynamic nature is incorporated into the respective analysis. The present study attempts to fill in this gap by developing a continuous monitoring system of environmental sensitivity to LDD of the island of Lesvos (Greece). We employ a modification of the MEDALUS approach, augmented with case-specific indices from DESERTLINKS (2004), and examine two different epochs.

MATERIALS AND METHODS

Area of study

Lesvos is an island of the Aegean Sea (Greece), in the eastern Mediterranean (Figure 1). It covers an area of approximately 1,633 km^2 and has a maximum altitude of 947 m. Typical of the Mediterranean region, the island's climate is characterised by strong seasonal and spatial variations of rainfall and high oscillations between minimum and maximum daily temperatures due to the regional effect of orography and atmospheric circulation patterns (Kosmas *et al.* 2000; Symeonakis *et al.*, 2012). Average annual rainfall ranges from 701 mm in the town of Agiasos in the east to 479 mm in Sigri in the west (Figure 1). Olive groves, Mediterranean maquis, phrygana, pine and deciduous oak forests as well as various types of agricultural uses dominate the landscape. Large parts of the terrain in Lesvos is ragged with steep slopes that favour the development of runoff and erosion. The majority of the island is covered by moderately deep soils although large parts, mainly in the western part, have shallow ones (<30cm; Kosmas *et al*. 1999b).

The study of Kosmas *et al.* (1999b) indicates that the majority of Lesvos is classified as critical or fragile to desertification and only 3.6% of the area is not threatened by desertification. The island is actually affected by the majority of the desertification issues and related problems that Zucca *et al.* (2011) identify in their extensive review of desertification-related published results of former projects and research, namely: inappropriate agricultural practices, increased soil erosion, overuse of water resources, salinization, grazing mismanagement, overgrazing and decreasing net primary productivity (NPP) in grasslands and shrublands, soil degradation, deforestation, increased aridity or drought, changes in population distribution and density, rural migration/land abandonment and urban sprawl (Giourga *et al*., 1994; Kosmas *et al.*, 1999b; Marianthou *et al.*, 2000; Koulouri & Giourga, 2007).

Monitoring Environmental Sensitivity

Environmental sensitivity is related to several bio-physical and anthropogenic factors, whose characteristics and intensity contribute to the evolution of different levels of degradation. In this study, the criteria outlined by Basso *et al.* (2000) were used for selecting the different layers of information for mapping sensitive areas according to the MEDALUS ESAI methodology (Kosmas *et al.* 1999a), namely: i) the relationship with the degradation phenomena; ii) the availability of data; iii) the ability of updating the datasets, and iv) the ability to refine, further develop or even remove existing layers of information in the future, if this is deemed important. Twenty-one layers belonging to five main environmental quality indices related with climate, vegetation, soil, groundwater and socio-economic characteristics of the land were estimated and their values standardized from 1 (least sensitive) to 2 (most sensitive) according to the ESAI (Kosmas *et al*., 1999a), DESERTLINKS (2004) and Sepehr *et al*. (2007; Tables 1 to 5). Ten indicators employed in this study have never been used before to appraise LDD sensitivity in Lesvos, namely soil water erosion, the groundwater quality-related indicators of sodium adsorption ratio, chloride concentration, electrical conductivity and water table height, and the socio-economic indicators of education level, old age index, population density, population growth, and sensitivity to grazing.

The five quality indices were estimated according to the ESAI methodology using the following formula (Figure 2):

$$QI\_k_{ij} = (\prod layer\_n_{ij})^{1/n} \tag{1}$$

where *QI_k* represents each of the quality indices and *i, j* represent rows and columns of each raster layer and *n* the number of layers used. In the last ESAI stage, the final sensitivity of an area is evaluated from the five quality indices in a linear way:

$$ESAI_{ij} = (\prod QI\_k_{ij})^{1/5} \qquad (2)$$

The ESAI assigns equal weights to each layer *n*, within each quality index (QI) *k*, as well as equal weights to each QI when computing the overall environmental sensitivity. This way, the computations in Equation 2 are unaffected by the number of layers used in every QI, which means that a QI is not considered of less importance because less layers are used for its computations, nor is a QI considered more important for the opposite reason (Basso *et al.* 2000). Tables 1 to 5 list the working set of thematic layers used in the GIS to assess environmental sensitivity in Lesvos together with the respective data and their sources.

Finally, the results were evaluated by comparing them to published 1:50,000 (finer-) scale results of environmental sensitivity in Lesvos by Kosmas *et al.* (1999b).

RESULTS AND DISCUSSION

The results for the five quality indices for the two epochs are shown in Figure 3. For simplicity, the first epoch is named '1990' and the second '2000', although some of the indicators are estimated with data from slightly different dates (e.g. the 1991 and 2001 census data). Moreover, to aid the discussion, the quantitative results are classified into three qualitative classes (low, moderate and high quality) according to the scheme suggested by Sepehr *et al.* (2007; Table 6).

In terms of the climate quality index, in 1990 (Figure 3a, Table 6) 10% of the island was mapped as having high climatic quality, 70% as moderate and 20% as low quality. In 2000 (Figure 3b, Table 6), the areas that were mapped as having a high quality in 1990, were 'shifted' to the moderate class thus increasing the proportion of the island with a moderate climatic quality to 80% of the total. This could be attributed to the fact that these areas, that cover the southeastern part of the island (from Plomari to Agiasos and further to the north of the capital Mytilene), received less precipitation in the second epoch. In both periods, the areas with the lowest climatic quality are found in the western part of the island around Eresos, in the central lowlands around Kalloni, and the eastern peninsula of Amali.

Figures 3c and 3e show that in both periods, the areas with low drought resistance (e.g. crops in the agricultural areas around Kalloni), with high fire risk (e.g. the pine forests in the west of Agiasos and the Amali peninsula) and with low percentage vegetation cover (e.g. in the west part around Eresos) are identified as highly sensitive in terms of their vegetation quality. The general picture between the two epochs is similar, especially with regards to the highly sensitive areas, which cover 41% of the island in both periods (Table 6). However, there is an increase in the amount of areas belonging to the high quality class from 4% to 11% and a subsequent decrease of 7% in the moderate quality areas (from 56% to 49%). This could again be attributed to the higher precipitation amounts in the second period which increased the percentage vegetation cover in the majority of the island. It could also be attributed to issues related with the estimation of vegetation cover directly from the satellite data and the NDVI. Although the NDVI has been extensively used in various studies to estimate green vegetation cover with satisfactory results, it has also been found that its application could be of limited use, especially in drier areas (Graetz *et al.*, 1986, Pickup *et al.*, 1993). Other authors, for example, have used empirical relationships between green vegetation cover and NDVI by measuring cover in the field and comparing it to satellite NDVI measurements (Zhang *et al.*, 2002; Symeonakis & Drake, 2004). Symeonakis *et al.* (2007) provide a summary of the techniques used in the literature for estimating vegetation cover from satellite data, other than the NDVI. However, the NDVI is by far the most widely used method for estimating green vegetation cover with satisfactory results, as demonstrated by the numerous regional- to global-scale studies (Albalawi and Kumar, 2013).

Soil quality (Figures 3e and 3f) is almost unchanged between 1990 and 2000. This is to be expected as four out of five indicators of the SQI are related with soil characteristics that are considered static in a ten-year period and only soil erosion was estimated separately for the two time steps. In 1990, 10% of the area of the island is covered by high quality soils, 72% by moderate and 18% by low (Table 6). These figures change to 13%, 73% and 15% in 2000. The areas with the most sensitive soils are found in the degraded western part of the island around Eresos, in the shallow, and often clay soils on steep slopes around Agiasos, the northwest and the southwest of Mytilene, and in the northwest of the island in shallow and relatively steep soils around Mythimna.

Groundwater quality is almost entirely moderate in both periods (Figure 3g and 3h, Table 6). More than 99% of the island, or 1632km^2 belong to this class in 1990 and 98% or 1611km^2 in 2000. There is a slight increase of the areas where the quality is higher in 2000 (26km^2 from 7km^2 in 1990) mostly in the north of the island, but also an area of 3km^2 (up from nearly zero in 1990) which appears to have a lower groundwater quality in 2000 and is located in the north of the city of Mytilene. This negative shift in ground water quality is due to the recorded increases in SAR, chloride concentration and electrical conductivity in the area.

In terms of the socio-economic dimension, there has been a noteworthy shift during the study period (Figure 3i and 3j, Table 6). In 1990, 90% of the island belonged to the moderate quality class, 8% to the high and 2% to the low. In 2000, the amount of low quality areas remained the same but the high quality areas increase by fourfold to 36% while the moderate quality ones where reduced to 62% of the island. The areas that improved are mainly situated in the western side of the island as well as around Polychnitos and north and northeast of Agiasos. The reason for this improvement can be attributed to the increase in education level as well as the slight improvement in the old age index across the municipalities in question. However, it is also due to the way the education level index is estimated by dividing the number of secondary education leavers (≥20 years old) to the total number of the population (≥20 years old). The latter is greatly affected by the rural-urban migration figures observed in the municipalities in question, i.e. the migration of the school leavers to the capital of the island (Mytilene) or the Greek capital, Athens, which in those years was preparing for the 2004 Olympic Games and was able to provide more employment opportunities.

The worsening of the socioeconomic quality in the eastern municipalities is due to the change in population dynamics in the region, i.e. the rapid growth of the population. This often uncontrolled and unplanned growth can put significant pressure on the natural resources, especially on the coastal rim where most of the tourist activities are focused but also due to the urban expansion towards the outskirts and the nearby towns of the island's capital, Mytilene. It is also worth noting here that changes in the sensitivity to grazing index between the two periods do not seem to affect the changes in the socio-economic index as a whole.

The environmental sensitivity of the island according to the ESA approach along with the changes in sensitivity between 1990 and 2000 are shown in Figures 4a to 4c. According to these results, the vast majority of the island is fragile or in a critical state in both periods: 81% in 1990 and 77% in 2000. Fragile areas, increase from 70% of the island to 71%. Non-affected areas are substantially less in 2000, covering 35km^2 from 60km^2 in 1990 and potentially sensitive areas increase from 15% to 20% of the island. There was an improvement in the island between the two epochs, in terms of the territory belonging to the 'critical' classes: areas in the C1 and C2 categories of the ESA classification decreased from 11% (162km^2) to 6% (90km^2). It is also worth noting that according to our findings, during the ten years studied here, the island does not include any areas that belong to the C3 most critically sensitive class of the ESA nomenclature (Figure 4).

The most sensitive parts of the island in both years are found in the south-western part of the island around Sigri, Eresos and Mesotopos, in the peninsula of Amali south of Mytilene and in the east of Tsilia. In 1990 the area around and to the west of Polichnitos towards Nyfida and further south to Cape Kalloni, is also mapped as critically sensitive. In 2000, a number of areas have become fragile on the eastern coast north of Mytilene. This can be attributed to the worsening of the groundwater quality and the rapid population increase in the area. On the contrary, some parts in the north show improvement in 2000 mainly due to increases in rainfall amounts and the subsequent increase in vegetation cover, as well as improved groundwater and socioeconomic qualities.

The results produced in this study for the 1990-2000 period corroborate the findings of previous work by Kosmas *et al.* (1999b) who applied the ESAI at the 1:50,000 scale. Both studies estimate that between 77% and 89% of the island is fragile or critically sensitive (our study: 77% in 2000, 81% in 1990; Kosmas *et al.* (1999b): 89%). Moreover, both studies also found that the western part of the island is the most sensitive. However, there are differences in the findings of the two studies, too, that could be attributed to the fact that the study by Kosmas *et al.* (1999b) does not include any of the parameters used here on groundwater quality, or the socio-economic parameters related with demographic characteristics and grazing, except for some information on the intensity of land use and the policy on land protection.

Caution must be applied to how our results are used as a number of shortcomings limit their interpretability. Firstly, the present pilot study was able to assess the proposed methodology only over a limited 10-year period, mainly due to the availability of groundwater data. Nevertheless, land degradation phenomena require larger time-scales to develop and the status and development of land degradation and desertification cannot be assessed during such short periods. Consequently, it is aimed to further test the methodology over a larger period when the ground water data become available. Secondly, the choice of the baseline year is also very important. The human-environment system is ever-changing due to its intrinsic natural fluctuations. Therefore, if a baseline year is not carefully chosen, then the assessment of the evolution of land degradation and desertification against it might be very misleading. In this study, it was not possible to define the baseline year from a careful examination of a longer period around this reference year, as suggested by Sommer *et al.* (2011). The baseline year, 1990, actually falls into a period of extended drought in the west of the island. This has distorted the outcome of the assessment of the trend of environmental sensitivity of the island.

Two issues related with data availability influenced the accuracy of the estimated indices and therefore the degree of environmental sensitivity. Firstly, all the layers of the climate quality index, were estimated using a sparse network of gauge stations, which possibly fail to represent the true range of climatic conditions of the island. Secondly, the livestock data available are at the sub-municipal level, which does not reflect the actual allocation of animals in the field. The animals in Lesvos, who usually graze in Mediterranean maquis, olive groves and garrigue land cover types, do not actually graze all possible grazing land, but only certain fields or plots of land that their owners consider appropriate (Kizos *et al*., 2013). Ideally, the data should list the number of animals per actual grazing field or plot, but this information is not available for Lesvos. Other methods of estimating the grazing pressure have been suggested such as the grazing gradient concept using cost surface modelling (Röder *et al.*, 2007) which employs, amongst other data, panchromatic very-high resolution Quickbird imagery for identifying points of livestock concentration. Unfortunately, such data were not available in this study.

The proposed methodology is based on the ESAI premise that any layers included must be simple, robust and widely applicable and that the choice of layers is made not only on the basis of importance but also by considering the ability to obtain and update them relatively easily and in an economically sound way. The ESAI also assumes that all indicators used in the system are equally important and hence, assigns an equal weight to them all. This issue has been identified as a flaw of the ESAI approach and was addressed initially by Salvati & Zitti (2009) and then by Salvati *et al.* (2009) and Salvati *et al.* (2011). These studies employed time-series multivariate statistical analyses to assign different weights to the individual indicators which undoubtedly converts the original methodology to a more complicated system involving several additional stages. However, Salvati *et al.* (2011) suggested that their approach is not an alternative to the ESAI, but that it could be used separately to provide further insight to the role of different land degradation processes affecting a certain area.

CONCLUSIONS

Land degradation and desertification affect large areas of Mediterranean Europe. The present study is an application of the widely used ESAI that incorporates additional bio-physical and socio-economic parameters for assessing the environmental sensitivity of the island of Lesvos. As a step forward from a previous application of the ESAI methodology in Lesvos by Kosmas *et al.* (1999b), here we used two different periods to study the dynamic nature of land degradation and desertification and incorporated additional information layers related to the prevailing processes in the study area, namely water erosion, groundwater-related parameters and socio-economic factors extracted from human and animal census data.

The vast majority of the island appears to be fragile or critically sensitive. The southwestern part of the island is the most sensitive, in agreement with the Kosmas *et al.* (1999b) study. However, by applying the modified ESAI methodology in two epochs this study was able to identify an area in the north of Mytilene that warrants attention, not because of its critical state, but because its sensitivity is increasing rapidly, mainly due to human-related factors linked to groundwater quality as well as demographic pressure.

The ESAI was designed to be a simple to use, easy to modify, GIS-based framework. With this in mind, the suggested methodology is able to provide a baseline for the appraisal of land degradation in Mediterranean environments and to predict improvement as well as degradation trends. The present study does not carry out a detailed analysis of the causes and manifestation of degradation which requires the acquisition and analysis of plot-scale data. Instead, this study has focused in the development of a system for the identification and monitoring of the sensitivity of areas to land degradation with a view to provide, through frequent, periodic updating of the database, a management tool of land degradation and desertification processes in Lesvos and similar Mediterranean islands and areas.

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Table 1. Main indicators, adopted classification scheme and scores from Kosmas *et al.* (1999b), and datasets and methods used in the GIS to estimate the Climate Quality Index

	Parameter	Classes	Score	Data/Source/Date
Climate Quality	**Rainfall** (mm)	>650	1	5 meteorological stations, mean monthly values for 1990-1995 and 1995-2000 (quality controlled, double mass curve) from Hellenic National Meteorological Service (EMY) and Division of Agriculture of the Prefecture of Lesvos (DAPL) Thiessen polygons interpolation
		280-650	1.5	
		<280	2	
	Aridity = Precipitation / Potential Evapotransp. (P/PET)	>0.65	1	Data for two periods: 1990-1995, 1995-2000 (source: EMY and DAPL) PET: FAO-56 Penman-Monteith equation (Allen *et al.*, 1998), mean monthly min & max temp. from five meteorological stations; Relative Humidity, Hours of Sunlight & Wind Speed: from one (Mytilene) station (only station with such records); Thiessen polygons interpolation
		0.5-0.65	1.5	
		<0.5	2	
	Aspect	N,NE,NW, plain (<5%)	1	30m-pixel DEM, Hellenic Military Geographical Service (HMGS)
		S,SE,SW	2	

Table 2. Main indicators, adopted classification scheme and scores from Kosmas *et al.* (1999b), and datasets and methods used in the GIS to estimate the Vegetation Quality Index

	Parameter	**Classes**	**Score**	**Data/Source/Date**
Vegetation Quality	**Drought resistance**	Evergreen forests (exc. coniferous); mixed Med. Maquis-evergreen forest (with Q. ilex); bedrock; bare soil	1	5 cloud-free late spring & summer Landsat 5 TM and Landsat 7 ETM+ data (path 181/row 33; Tucker *et al.*, 2004) for mapping the main land cover classes: 11/5/1987; 7/8/1990; 4/7/1995; 28/5/1999; 26/6/2001 Multi-temporal classification approach (Kiiveri *et al.*, (2001) and Caccetta *et al.* (2007). Overall size of the mean errors (RMSE) for ortho-rectification <1 pixel; Overall accuracies after multi-temporal classification: 85% to 87% for all imagery
		Conifer forests; Deciduous forests; Olives	1.2	
		Almonds; Orchards; Vines	1.4	
		Perennial grasslands; Pastures; Shrublands	1.7	
		Annual crops (annual grassland; cereals; maize; sunflower); Horticulture; Very low vegetated	2	
	Erosion protection	Evergreen forest (except conifers); mixed Med. Maquis-evergreen forest (with Q. ilex); Bedrock	1	
		Med. Macquis; Conifer forests; Perennial grasslands; Pastures; Olives; Shrubs	1.3	
		Deciduous forests (oak, mixed).	1.6	
		Almonds; Orchards	1.8	
		Vines; Horticulture; Annual crops; Very low vegetated; Bare soils	2	
	Fire risk	Bare soils; Bedrock; Almonds; Orchards; Vines; Olives; Irrigated annual crops; Horticulture	1	
		Perennial grasslands; Pastures; Cereals; Annual grasslands; Deciduous forests (oak, mixed); Mixed Mediterranean Maquis-Evergreen forests (with Q. ilex); Very low vegetated; Shrublands	1.3	
		Mediterranean Maquis	1.6	
		Pines and other conifer forests	2	
	Plant cover (%)	>40	1	Scaled Normalised Difference Vegetation Index (scaled-NDVI) or N* (Carlson *et al.*, 1995) applied to the 7/8/1990 and 26/6/2001 Landsat imagery. VC = 100 * N*= 100 * [(NDVI- NDVIo)/ (NDVIs-NDVIo)] where NDVI = (band 4 – band 3)/(band 4 + band 3); NDVIs is the value of NDVI at 100% VC (N*= 1.0) and NDVIo is that value for bare soil (N*= 0)
		10-40	1.8	
		<10	2	

Table 3. Main indicators, adopted classification scheme and scores from Kosmas *et al.* (1999b), and datasets and methods used in the GIS to estimate the Soil Quality Index. For Water Erosion, 5 quantile classes were used and the standardisation scheme suggested by Sepehr et al. (2007).

	Parameter	Classes	Score	Data/Source/Date
Soil Quality	**Parent material**	Shale; schist; basic; ultra basic; conglomerates; unconsolidated; clays; marl (with natural veg.)	1	1:50,000 Geological Map, Institute of Geology & Mineral Exploration (IGME)
		Limestone; marble; granite; rhyolite; ignibrite; gneiss; siltstone; sandstone; dolomyte	1.7	
		Marl; Pyroclastics	2	
	Texture	L,SCL,SL,LS,CL	1	1: 500,000 General Soil Map of Greece (Nakos, 1979)
		SC,SiL,SiCL	1.2	
		Si,C,SiC	1.6	
		S	2	
	Soil depth (cm)	>75	1	1: 50,000 Soil Map of Greece (Vardakis *et al.*, 1993) 213 field measurements (this research)
		30-75	1.2	
		15-30	1.6	
		<15	2	
	Water erosion (mm/year)	<0.0001	1.0	1: 500,000 General Soil Map of Greece Nakos (1979); 30m-pixel Landsat TM and ETM+, 7/8/1990 and 26/6/2001 (Tucker *et al.*, 2004); Thornes (1990) soil erosion model (Symeonakis *et al.*, 2007; Symeonakis & Drake, 2010): $E = k\,Q^2\,s^{1.67}\,e^{-0.07VC}$ where E is erosion (mm), k is soil erodibility coefficient, Q is runoff (mm) and s is slope (%).
		0.0001-0.0087	1.2	
		0.0087-0.026	1.5	
		0.026-0.07	1.7	
		>0.07	2.0	
	Slope gradient	<6	1	30m-pixel DEM (HMGS)
		6-18	1.2	
		18-35	1.5	
		>35	2	

Table 4. Main indicators, adopted classification scheme and scores from Sepehr *et al.* (2007), and datasets and methods used in the GIS to estimate the Groundwater Quality Index

	Parameter	Classes	Score	Data/Source/Date
Groundwater Quality	Water table depth (m)	>3.15	1	341 measurements of the Institute of Geology & Mineral Exploration (IGME) (Kammas & Kaloumenos, 2002) for two periods: 1990-1995 and 1995-2000; Inverse distance weighted (IDW) interpolation
		2.85-3.15	1.5	
		<2.85	2	
	Sodium Adsorption Ratio (SAR; $meq/l^{0.5}$)	<10	1	
		10-18	1.3	
		18-26	1.6	
		>26	2	
	Chloride concentration (mg/l)	<250	1	
		250-500	1.2	
		500-1500	1.5	
		1500-3000	1.7	
		>3000	2	
	Electrical conductivity (μmohs/cm)	<250	1	
		250-750	1.2	
		750-2250	1.5	
		2250-5000	1.7	
		5000	2	

Table 5. Main indicators, adopted classification scheme and scores from DESERTLINKS (2004), and datasets and methods used in the GIS to estimate the Socio-economic Quality Index. For Population Growth Rate and Old Age, equal-interval classes were used for classifying and standardizing the data. For Sensitivity to Grazing, quartile classes and a common standardisation scheme used by the ESAI.

	Parameter	Classes	Score	Data/Source/Date
Socio-economic Quality	Population density (people per km²)	<25	1	Census data for 1991 and 2001 at the sub-municipal level Hellenic Statistical Authority (EL.STAT.)
		25-50	1.2	
		50-100	1.4	
		100-200	1.6	
		200-400	1.8	
		>400	2	
	Population growth rate (%)	<2	1	
		2-4	1.2	
		4-6	1.4	
		6-8	1.6	
		8-10	1.8	
		>10	2	
	Old age	<200	1	old age index = (inhabitants >65) / (inhabitants <5)
		200-400	1.3	
		400-500	1.6	
		>500	2	
	Education level (%)	>35	1	education level = (inhabitants >20 that are secondary education leavers) / (inhabitants > 20)
		30-35	1.2	
		25-30	1.4	
		20-25	1.6	
		15-20	1.8	
		<15	2	
	Sensitivity to grazing (sheep and goats per km²)	<0.0066	1	Census of agricultural & livestock holdings data for 1991 and 2001 at the sub-municipal level (EL.STAT.) Census data correlated with % vegetation cover (VC), a modification of the methodology suggested by Papanastasis (2000): Sensitivity to grazing = (100 - VC) * (nsg /a) where :n_{sg} is total number of sheep and goats; *a* the area and *VC* the percent vegetation cover of potential grazing land cover types. For Lesvos, these include Mediterranean maquis, olive groves and scrubland
		0.0066-0.13	1.3	
		0.013-0.019	1.6	
		>0.019	2	

Table 6. Percentage of the land area covered by each sensitivity class of the five quality indices in 1990 and 2000, according to the classification scheme suggested by Sepehr *et al.* (2007)

Quality Index	Range	Sensitivity Class	1900 (%)	2000 (%)
Climate Quality Index (CQI)	1	Low	10.9	0.0
	1.1-1.5	Moderate	69.5	80.4
	1.6-2	High	19.6	19.6
Vegetation Quality Index (VQI)	<1.13	Low	3.6	10.6
	1.13-1.38	Moderate	55.6	48.6
	>1.38	High	40.8	40.8
Soil Quality Index (SQI)	<1.13	Low	10.5	12.5
	1.13-1.45	Moderate	71.3	72.8
	>1.46	High	18.2	14.7
Groundwater Quality Index (GQI)	1	Low	0.4	1.5
	1-1.4	Moderate	99.5	98.3
	>1.4	High	0.1	0.2
Socio-economic Quality Index (SosQI)	1-1.13	Low	8.4	36.1
	1.3-1.5	Moderate	89.9	61.7
	>1.5	High	1.7	2.2

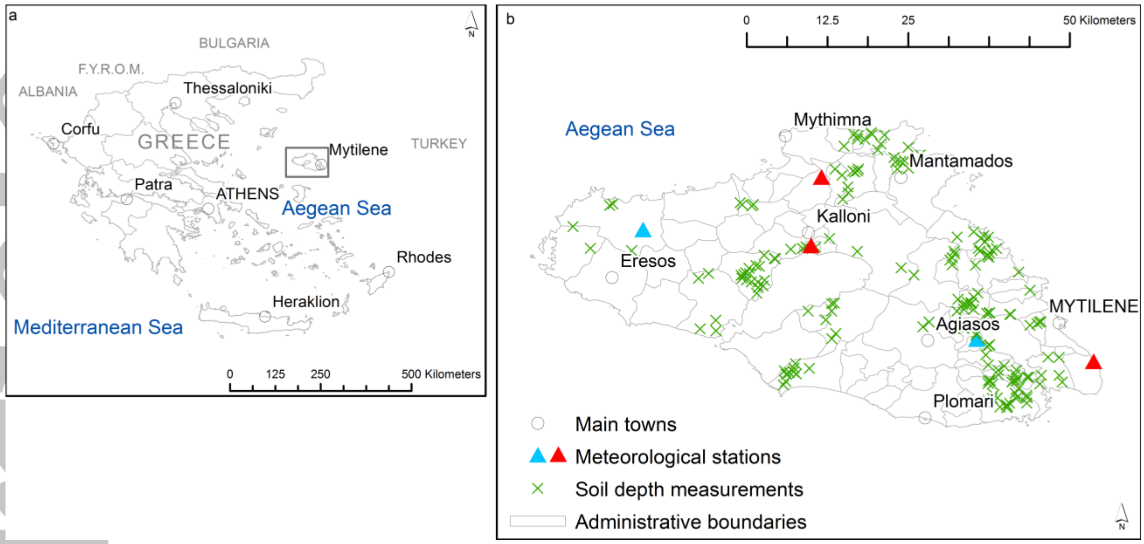

Figure 1. (a) The location of the study area, the island of Lesvos, in the Aegean Sea, Greece. (b) Locations of meteorological stations, soil depth field measurements, main localities and administrative sub-municipal boundaries. The subset of red stations are the ones used for the estimation of potential evapotranspiration.

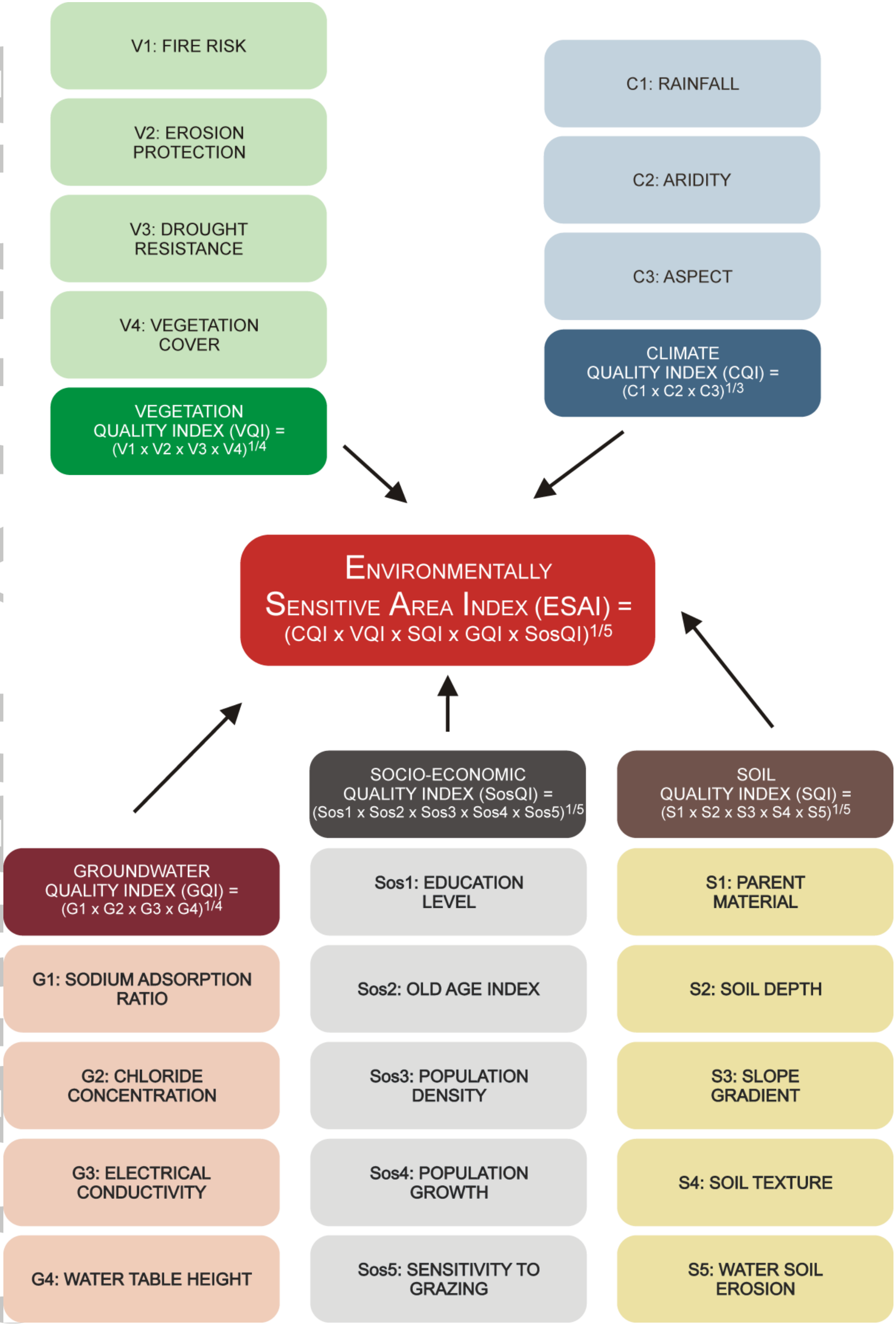

Figure 2. Flowchart of the methodological framework for the estimation of the modified Environmentally Sensitive Area Index (ESAI).

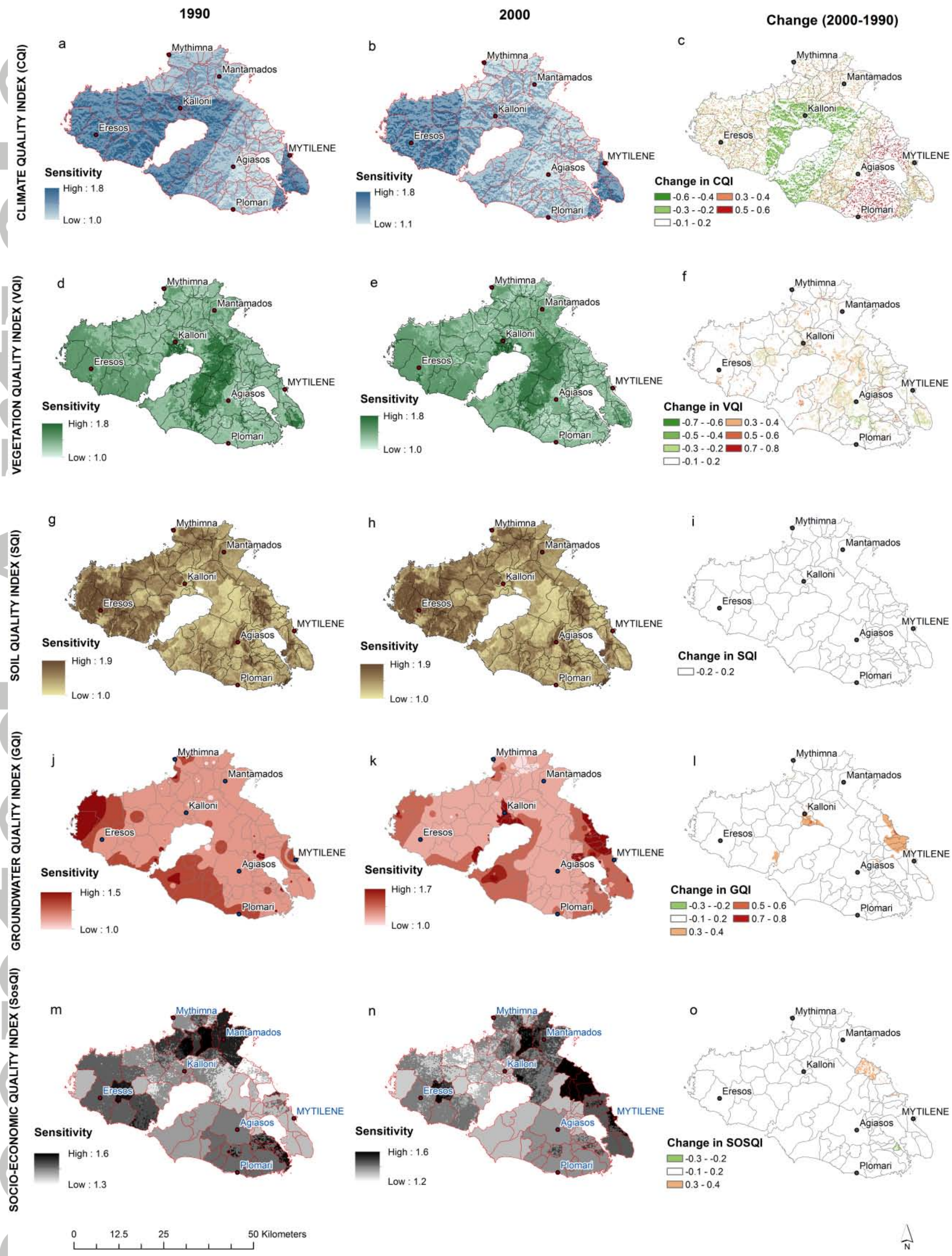

Figure 3. Sensitivity maps for 1990 and 2000 and respective change: (a), (b), (c) Climate Quality Index (CQI); (d), (e), (f) Vegetation Quality Index (VQI); (g), (h), (i) Soil Quality Index (SQI); (j), (k), (l) Groundwater Quality Index (GQI); (m), (n), (o) Socioeconomic Quality Index (SosQI).

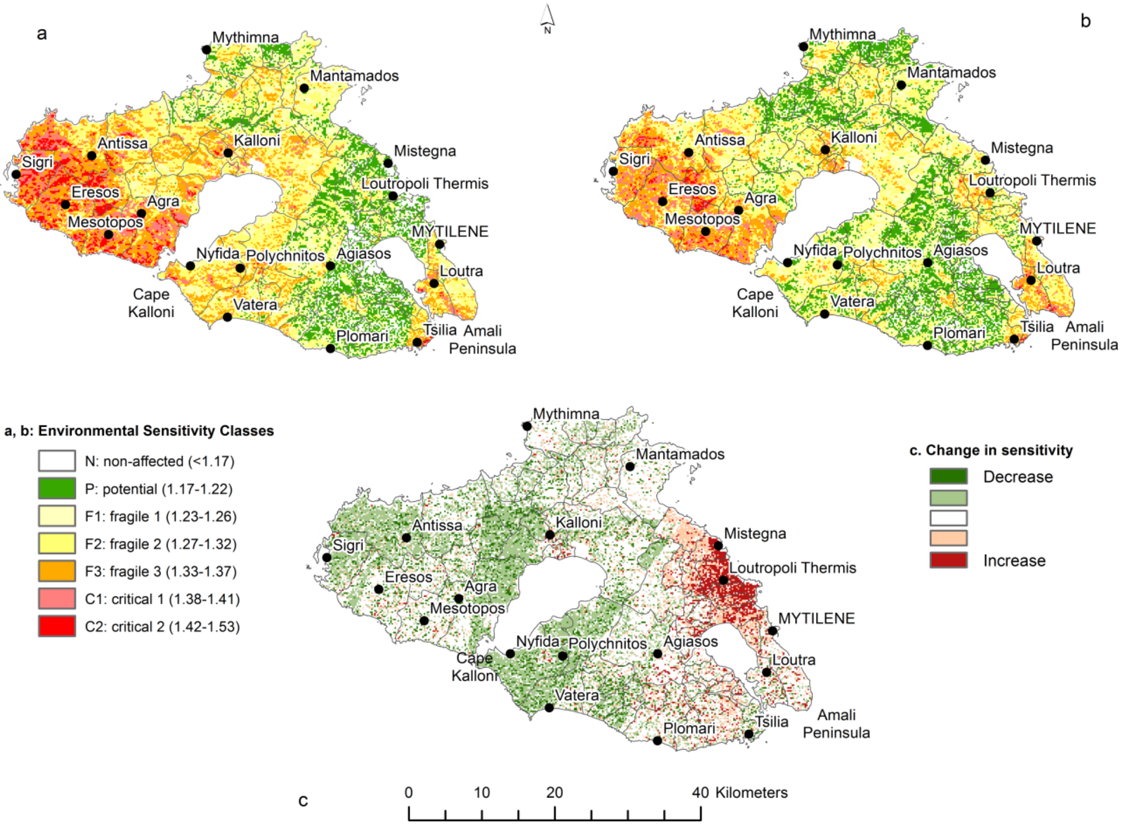

Figure 4. Environmental sensitivity according to the ESAI for (a) 1990 and (b) 2000. (c) Change in sensitivity between 1990 and 2000.