Environmental Management
DOI 10.1007/s00267-013-0109-6

Evaluation and Selection of Indicators for Land Degradation and Desertification Monitoring: Methodological Approach

C. Kosmas · Or. Kairis · Ch. Karavitis · C. Ritsema · L. Salvati · S. Acikalin · M. Alcalá · P. Alfama · J. Atlhopheng · J. Barrera · A. Belgacem · A. Solé-Benet · J. Brito · M. Chaker · R. Chanda · C. Coelho · M. Darkoh · I. Diamantis · O. Ermolaeva · V. Fassouli · W. Fei · J. Feng · F. Fernandez · A. Ferreira · C. Gokceoglu · D. Gonzalez · H. Gungor · R. Hessel · J. Juying · H. Khatteli · N. Khitrov · A. Kounalaki · A. Laouina · P. Lollino · M. Lopes · L. Magole · L. Medina · M. Mendoza · P. Morais · K. Mulale · F. Ocakoglu · M. Ouessar · C. Ovalle · C. Perez · J. Perkins · F. Pliakas · M. Polemio · A. Pozo · C. Prat · Y. Qinke · A. Ramos · J. Ramos · J. Riquelme · V. Romanenkov · L. Rui · F. Santaloia · R. Sebego · M. Sghaier · N. Silva · M. Sizemskaya · J. Soares · H. Sonmez · H. Taamallah · L. Tezcan · D. Torri · F. Ungaro · S. Valente · J. de Vente · E. Zagal · A. Zeiliguer · W. Zhonging · A. Ziogas

Received: 9 July 2012 / Accepted: 7 June 2013

Abstract An approach to derive relationships for defining land degradation and desertification risk and developing appropriate tools for assessing the effectiveness of the various land management practices using indicators is presented in the present paper. In order to investigate which indicators are most effective in assessing the level of desertification risk, a total of 70 candidate indicators was selected providing information for the biophysical environment, socio-economic conditions, and land management characteristics. The indicators were defined in 1,672 field sites located in 17 study areas in the Mediterranean region, Eastern Europe, Latin America, Africa, and Asia. Based on an existing geo-referenced database, classes were

C. Kosmas (✉) · Or. Kairis · Ch. Karavitis · V. Fassouli · A. Kounalaki
Laboratory of Soils, Agricultural University of Athens,
Iera Odos 75, 118 55 Athens, Greece
e-mail: ckosm@aua.gr

C. Ritsema · R. Hessel
Alterra, Wageningen, UR, The Netherlands

L. Salvati
Italian National Council for Agricultural Research, Rome, Italy

S. Acikalin · C. Gokceoglu · H. Gungor · F. Ocakoglu · H. Sonmez · L. Tezcan
Eskisehir Osmangazi University, Eskisehir, Turkey

M. Alcalá · D. Gonzalez · L. Medina · M. Mendoza · C. Prat · A. Ramos · J. Ramos
Institut de Recherche pour le Développement, Mexico City, Mexico

P. Alfama · J. Brito · N. Silva
National Institute for Agriculture Research and Development, Praia, Cape Verde

J. Atlhopheng · R. Chanda · M. Darkoh · L. Magole · K. Mulale · J. Perkins · R. Sebego
University of Botswana, Francistown, Botswana

J. Barrera · F. Fernandez · C. Ovalle · C. Perez · A. Pozo · J. Riquelme · E. Zagal
Instituto de Investigaciones Agropecuarias, Santiago, Chile

A. Belgacem · H. Khatteli · M. Ouessar · M. Sghaier · H. Taamallah
Institut Des Regions Arides, Medinine, Tunisia

A. Solé-Benet · J. de Vente
Estacion Experimental de Zonas Áridas (EEZA-CSIC),
La Cañada de San Urbano, Spain

M. Chaker · A. Laouina
Chair UNESCO-GN, University of Mohamed V, Rabat, Morocco

C. Coelho · J. Soares · S. Valente
University of Aveiro, Aveiro, Portugal

I. Diamantis · F. Pliakas · A. Ziogas
Democritus University of Thrace, Komotini, Greece

designated for each indicator and a sensitivity score to desertification was assigned to each class based on existing research. The obtained data were analyzed for the various processes of land degradation at farm level. The derived methodology was assessed using independent indicators, such as the measured soil erosion rate, and the organic matter content of the soil. Based on regression analyses, the collected indicator set can be reduced to a number of effective indicators ranging from 8 to 17 in the various processes of land degradation. Among the most important indicators identified as affecting land degradation and desertification risk were rain seasonality, slope gradient, plant cover, rate of land abandonment, land-use intensity, and the level of policy implementation.

Keywords Indicators · Land degradation · Desertification risk

Introduction

Land degradation and desertification are among the most serious environmental issues at global, regional, and local scales (UNEP 1992; Imeson 1996). Both are global processes that are especially active in arid, semi-arid, and dry sub-humid areas, and that have been enhanced in recent decades by factors including climatic variations and human activities. An assessment carried out by the Food and Agriculture Organization of the United Nations (FAO) based on data collected during the "Global Assessment of Soil Degradation—GLASOD" (Oldeman 1988; Oldeman and others 1990) showed that 19.5 % of dry lands were affected by soil degradation. A subsequent study (Dregne and others 1991), carried out by the International Centre for Arid and Semi-Arid Land Studies (ICASALS), revealed that approximately 70 % of arid lands show more or less intense signs of desertification. Moreover, cropland experiences the highest risk, approximately 70 % of which may already be degraded. Land degradation and desertification affect over one billion people (Rubio and Recatala 2006).

Desertification has been and still is a controversial issue. In the previous decades, this was largely due to the lack of a common understanding of "what to measure" and "how to measure it". In the 1970s, the desertification indicators sought were those able to measure the advance of the desert. During the 1980s the need for a general and flexible approach to combat desertification became more keenly felt. Desertification of an area will proceed if certain land components degraded beyond specific thresholds, leading to irreversible further change (Kosmas and others 1999). Indicators of desertification may demonstrate that desertification has already proceeded to its end point of irreversibly unproductive soil.

The necessity of elaborating indicators is one of the priorities identified by the United Nations Convention to Combat Desertification (UNCCD) (COP9 2009). Indicators generally simplify reality to make complex processes quantifiable so that the information obtained can be communicated (EEA 2005). There is always a possibility for inaccuracy associated with indicators but this can be taken into account sometimes as degree of risk. However, it is usually more meaningful to use indicators than try and interpret huge numbers of individual pieces of data. The identification of truly valid indicators will insure the most effective use of limited data provided by monitoring systems as well as of allocated resources. The most useful indicators, however, are those which indicate the potential risk of desertification while there is still time and scope for remedial action.

Rubio and Bochet (1998) tackled the subject of desertification indicators in considerable detail and proposed a synthesized list of criteria, and a procedure for the selection, evaluation, and application of indicators. A notable attempt to define environmentally sensitive areas (ESAs) to desertification was made in the context of the "MEDALUS" research project (Kosmas and others 1999). In that approach a set of key indicators describing different desertification factors (climate, soil, vegetation, management) are used to derive a composite index of land desertification. Although the ESAs methodology was widely used for over a decade directly or indirectly (e.g., Salvati 2011), some researchers claimed that it contained a lack of socio-economic variables such as population density, population growth rate, etc. (Salvati and others 2008; Salvati and Bajocco 2011). Recatala and others (2002) reported environmental indicators to assess and monitor land desertification and its influence on environmental quality in Mediterranean ecosystems. The EU funded DESERTLINKS research project interviewed many stakeholders in areas affected by desertification after which a long list of more than 150 candidate indicators of desertification was identified and described in the DIS4ME online system (Brandt and Geeson 2005) (http://www.kcl.ac.uk/projects/desertlinks/accessdis4me.htm). This system which

O. Ermolaeva · N. Khitrov · V. Romanenkov · M. Sizemskaya · A. Zeiliguer
Moscow State University of Environmental Engineering, Moscow, Russia

W. Fei · J. Feng · J. Juying · Y. Qinke · L. Rui · W. Zhongping
Institute of Soil and Water Conservation, Yangling, China

A. Ferreira · M. Lopes · P. Morais
Escola Superior Agraria de Gois, Coimbra, Portugal

P. Lollino · M. Polemio · F. Santaloia · D. Torri · F. Ungaro
Research Institute for Hydrogeological Protection, Firenze, Italy

is publicly available includes many simple indicators, some key headline indicators (simple indicators integrating several aspects of a more complex system) as well as composite indices.

The data required to support an indicator should be: (a) readily available or made available at a reasonable cost/benefit ratio, (b) adequately documented and of known quality, and (c) updated at regular intervals in accordance with reliable procedures. The establishment of an indicator monitoring system for environmental purposes is also dependent on the geographical scale. Some indicators such as rain seasonality or drainage density are useful over large areas, but others such as soil depth, vegetation cover type, and land ownership are only applicable locally. In order to practically enhance the sustainability of land management, research on using indicators for assessing land degradation and desertification risk must initially focus at farm level because management decisions by individual land users are taken at this level. However, as Allen and others (1995) states, decision-makers and the public also need a limited number of highly aggregated indicators. This means that data collection may involve a large number of indicators but the final presentation should include a few aggregated indices that may be easily understood and can be compared to determine environmental trends. Aggregate indices can provide simple and clear information to decision-makers and the general public about progress in environmental policies. A simple indicator can be a sign of desertification risk for the land owner. It can be definitely assessed that there will be a risk of desertification only after combining with other indicators such as annual rainfall, slope gradient, etc. The key objective of the research described in this paper was to derive a methodology for the assessment of land degradation and desertification risk in areas prone to desertification using simple indicators. An extensive description of the results obtained with the method, and what these results say about degradation processes and causes, is given in Kairis and others (this issue).

Methods

Defining a List of Indicators

An integrated approach incorporating indicators from various sources and used for assessing the stage of land degradation and desertification has been developed within the framework of the DESIRE project (Hessel and others this issue). The list of candidate indicators (Table 1) was compiled by: (a) reviewing literature (Kosmas and others 1999; Enne and Zucca 2000; Wascher 2000; Organization for Economic Co-operation and Development-OECD 2004; Liniger and others 2007), (b) consulting with stakeholders including land users, land managers, and research groups working on land degradation and desertification issues both internationally and in each study area, and (c) using previous research carried out in research projects on land degradation and desertification (e.g., MEDALUS III-ENV4-CT95-0119, MEDRAP–EVK2-CT-2000-20 008, DESERTLINKS—EVK2-CT-2001-00109). Details about the range of stakeholders are available in the DESIRE-HIS (http://www.desire—his.eu/en/study-sites).

Focus group meetings were organized in which participants were asked to provide their opinion about environmental security and the use of indicators for protection against desertification. A questionnaire on candidate indicators was discussed with various stakeholders (farmers, administrators, scientists). The list is the result of combining scientific indicators, such as aridity index, with indicators that stakeholders feel are relevant, such as water quality or soil depth. A detailed description of the various indicators used in this study is available in the DESIRE project website (http://www.desire-his.eu/en/themes).

The main processes or causes of land degradation and desertification identified in the 17 DESIRE study sites (see "Description of the study sites" section for details on the study sites) were: (a) soil erosion including water and tillage erosion, (b) soil salinization, (c) water stress, (d) forest fires, and (e) overgrazing. Based on expert opinion of people of DESIRE study sites, the candidate indicators were allocated among the various processes or causes of land degradation for further analysis (Table 1, checked by ◆).

Included in the list of candidates are various indicators such as: (a) state indicators that allow monitoring of the success of mitigation measures; these need to be tailored for maximum sensitivity to each particular technique, (b) driver and pressure indicators focusing on conditions where remedial intervention may be needed to prevent land degradation and desertification, and (c) response indicators characterizing actions undertaken for land protection. Furthermore, the analysis included indicators related to local (farm) level, such as Land use type, Farm size Tillage operations, or regional conditions (municipality, watershed) such as Farm subsidies allocated, or Rainfall seasonality.

For each indicator the range of possible values was grouped into four or five classes (Table 2) using existing classification systems such as the European geo-referenced soil data base (Van Engelen and Wen 1995; Finke and others 1998; Kosmas and others 1999; Van Engelen and others 2005; Liniger and others 2007), and existing research data (Kosmas and others 1999; Kosmas and others 2000a and Kosmas and others 2000b; Brandt and Geeson 2005). Sensitivity scores in the range 1.0–2.0 were assigned to each class based on existing research data or on the importance to land degradation and desertification. Definition of class

Table 1 List of candidate indicators related to causes or processes of land degradation and desertification in the study sites

Indicators	Processes important for desertification in study sites					
	Water erosion	Tillage erosion	Soil salinization	Water stress	Forest fires	Over-grazing
Physical and ecological indicators						
Climate						
Air temperature			◆	◆	◆	◆
Rainfall	◆	◆	◆	◆	◆	◆
Aridity index			◆	◆	◆	◆
Potential evapotranspiration	◆		◆	◆	◆	◆
Rainfall seasonality	◆		◆	◆	◆	◆
Rainfall erosivity	◆					◆
Water						
Water quality			◆	◆		
Water quantity			◆	◆		
Groundwater exploitation			◆	◆		
Water consumption/water demands			◆	◆		
Soils						
Drainage			◆	◆		
Parent material	◆	◆	◆	◆		◆
Rock fragments	◆	◆		◆		◆
Slope aspect	◆			◆	◆	◆
Slope gradient	◆	◆		◆		◆
Soil depth	◆	◆	◆	◆	◆	◆
Soil texture	◆	◆	◆	◆		◆
Soil water storage capacity	◆		◆	◆		◆
Exposure of rock outcrops	◆			◆		◆
Organic matter surface horizon	◆	◆				◆
Electrical conductivity			◆			
Vegetation						
Prevalent land cover	◆	◆		◆	◆	◆
Vegetation cover type	◆			◆	◆	◆
Plant cover	◆			◆	◆	◆
Deforested area				◆	◆	◆
Water runoff						
Drainage density	◆			◆		
Flooding frequency			◆			
Impervious surface area	◆			◆		
Fires						
Fire frequency				◆	◆	◆
Fire risk					◆	◆
Burned area	◆				◆	◆
Socio-economic indicators						
Agriculture						
Farm ownership	◆		◆		◆	◆
Farm size	◆					◆
Land fragmentation	◆					◆
Net farm income	◆				◆	◆
Parallel employment	◆			◆		◆
Cultivation						
Tillage operations	◆	◆		◆		

Table 1 continued

Indicators	Processes important for desertification in study sites					
	Water erosion	Tillage erosion	Soil salinization	Water stress	Forest fires	Over-grazing
Tillage depth	◆	◆				
Tillage direction	◆	◆				
Mechanization index		◆				
Husbandry						
Grazing control	◆			◆	◆	◆
Grazing intensity	◆			◆	◆	◆
Land management						
Fire protection	◆			◆	◆	◆
Sustainable farming	◆					
Reclamation of affected areas			◆			
Reclamation of mining areas	◆				◆	
Soil erosion control measures	◆	◆		◆	◆	◆
Soil water conservation measures	◆			◆		◆
Terracing (presence of)	◆	◆		◆		◆
Land use						
Land abandonment	◆			◆	◆	◆
Land use intensity	◆	◆		◆	◆	◆
Land use type	◆		◆	◆	◆	
Period of existing land use	◆		◆			
Distance from seashore			◆			
Water use						
Aquifer over exploitation			◆	◆		
Irrigation percentage of arable land	◆		◆	◆		
Runoff water storage	◆			◆		◆
Water consumption by sector				◆		
Water scarcity			◆	◆	◆	◆
Tourism						
Tourism intensity	◆		◆	◆	◆	
Tourism change				◆	◆	
Social						
Human poverty index				◆	◆	
Old age index	◆			◆		◆
Population density	◆		◆	◆	◆	◆
Population growth rate	◆			◆		◆
Population distribution						
Institutional						
Farm subsidies	◆					◆
Protected areas					◆	◆
Policy implementation	◆	◆	◆	◆		◆

boundaries introduces a level of subjectivity, which is considered justifiable for application to a wide range of environments and socio-economic conditions. Besides, it scales the values of the different indicators to comparable ranges and therefore prevents absolute indicator values determining the coefficients of the equations that were developed. In addition, it allows comparison between different regions and a similar weighting system has been successfully used in the definition of ESA to desertification that has been widely applied in the Mediterranean region and elsewhere (Salvati and others 2008; Benabderrahmane and Chenchouni 2010; Parvari and others 2011).

Defining Desertification Risk

Five categories of desertification risk were distinguished, namely: very high, high, moderate, low, and none. Coefficients were assigned for each category of desertification risk ranging from 1 (no risk) to 5 (very high risk). The description of each category of desertification risk follows in Table 3. An empirical approach was adapted to define categories of desertification risk based on the type of ESA to desertification (Kosmas and others 1999), and on the main process or cause of degradation identified for each study site (e.g., degree of soil erosion, soil water storage capacity, and soil electrical conductivity). The type of ESA in combination with the degree of soil erosion, water storage capacity, and soil electrical conductivity or the relevant processes or causes of land degradation, the risk of land desertification has been assessed. For example, an area characterized as sensitive to desertification will experience high desertification risk under severe erosion or low risk under slight erosion. The degree of soil erosion has been mainly considered for hilly areas, while soil electrical conductivity has been used mainly in plains where the dominant process of desertification was soil salinization. Soil water storage capacity was considered for hilly areas or plains where water stress was the dominant process of land degradation and desertification.

The concept of desertification risk summarizes the vulnerability or sensitivity of the land to further degradation and desertification according to existing land, socio-economic, and management characteristics. The definition of the present stage of desertification can be assessed by incorporating soil, vegetation, climate, and management indicators in the previously developed methodology for ESAs. This methodology has been developed for Mediterranean Europe but has been successfully tested in other parts of the world affected by desertification (Sepehr and others 2007; Benabderrahmane and Chenchouni 2010; Parvari and others 2011).

Description of the Study Sites

In the framework of the DESIRE project, a total of 17 study sites were selected located in areas vulnerable to desertification in various parts of the Mediterranean and Eastern Europe, Latin America, Africa, and Asia: (1) Rendina basin Basilicata-Italy, (2) Nestos basin Maggana-Greece, (3) Crete island-Greece, (4) Mação area-Portugal, (5) Gois area-Portugal, (6) Guadalentin basin SE-Spain, (7) Konya Karapinar plain-Turkey, (8) Eskisehir plain-Turkey, (9) Novij Saratov-Russia, (10) Djanybek area-Russia, (11) Zeuss Koutine-Tunisia, (12) Boteti area-Botswana, (13) Santiago island-Cape Verde, (14) Mamora Sehoul-Morocco, (15) Loess Plateau-China, (16) Secano Interior-Chile, and (17) Cointzio catchment-Mexico (Fig. 1). In all study sites, field surveys were conducted in different land-use types such as olive groves, vineyards, cereals, almonds, cotton, pastures, deciduous forests, pine forests to obtain the values of indicators at a number of sampling points.

The study sites are characterized by a variety of physical environment, social and economic conditions (Hessel and others this issue). They are located in areas affected by or sensitive to land degradation and desertification from a variety of processes and causes, such as soil erosion, soil salinization, water stress, overgrazing, forest fires, and urbanization. The climatic conditions of the study sites are mainly semi-arid or dry sub-humid with annual rainfall ranging from 280 to 1,000 mm, with Bagnouls-Gaussen aridity index usually >125. The most important classes of air temperature are <12 °C, 15–18 °C, and >21 °C. The rain seasonality is mainly characterized as seasonal to marked seasonal with a long dry season.

Across all study sites, the soils were mainly well to imperfectly drained, formed mainly on sedimentary and unconsolidated parent materials, free of rock fragments to moderately stony. Soil depth is mainly characterized as deep to very deep in 52 % of the sampling points with moderately fine to fine textures in 56 % of the points. Slope gradients greater than 12 % were documented in 58 % of them. Soils were moderately to severely eroded in 72 % of the points. Finally, study sites in which soil salinization was the most important process of land degradation had mainly low to moderate Electrical conductivity. The existing vegetation consists mainly of agricultural crops in 51 % of the points, with pastures in 25 %. Agricultural vegetation cover types are: cereals (33 %), olives (18 %), vines (18 %), cotton (10 %), with soil cover <50 %, in 51 % of the points.

Data Collection and Analysis

Questionnaires were prepared separately for each land degradation process or cause, including the indicators identified in Table 1. Questionnaires were completed at 1,672 sampling points (combination of land-uses and process) in the 17 study sites. Data related to water erosion were further subdivided based on the prevalent land-use types (agriculture, pasture, and forest). This distinction was made for a more appropriate use of certain indicators such as Tillage operations, Tillage direction, which are very important for agricultural areas, but not for forested ones, while the indicators Grazing intensity, and percent Burned area are more significant for pastures or forested areas, but not for agricultural areas. To harmonize data collection between the study sites, a manual was compiled defining each indicator and describing the methodology or technique for measuring its values (http://www.desire-his.eu/en/assessment-with-indicators/wp21-identifying-indicators-

Table 2 List of indicators with distinct classes for each indicator and the related sensitivity score

Climate							
Annual air temperature (°C)	<12	12–15	15–18	18–21	>21		
	1.0	1.8	1.5	1.8	2.0		
Annual rainfall (mm)	<280	280–650	650–1000	>1000			
	2	1.6	1.3	1.0			
BG aridity index	<50	50–75	75–100	100–125	125–150	>150	
	1.0	1.2	1.4	1.6	1.8	2.0	
Annual pot. evapotranspiration (ETo) (mm)	<500	500–800	800–1200	1200–1500	>1500		
	1.0	1.2	1.5	1.8	2.0		
Rain seasonality	<0.19	0.20–0.39	0.40–0.59	0.60–0.79	0.80–0.99	1.00–1.19	>1.20
	1.0	1.2	1.4	1.6	1.8	1.9	2.0
Rain erosivity (mm h^{-1})	<60	60–90	91–120	121–160	>160		
	1.0	1.2	1.5	1.8	2.0		
Water							
Water quality (µS)	<400	400–800	800–1500	>1500			
	1.0	1.3	1.6	2.0			
Water quantity	Adequate	Moderate	Low	None			
	1.0	1.3	1.6	2.0			
Ground water exploitation	Exploitation > recharge	Recharge > exploitation >0.8·recharge	Local problems of over-exploitation	Without problems of over-exploitation			
	2.0	1.6	1.3	1.0			
Water consumption/water demands (WC/WD)	Low (WC/WD < 0.5)	Moderate (WC/WD = 0.5–1)	High (WC/WD=1-2)	Very high (WC/WD>2)			
	1.0	1.3	1.6	2.0			
Soils							
Drainage	Well	Imperfectly	Poorly	Very poorly			
	1.0	1.3	1.6	2.0			
Parent material	Limestone-marble	Acid igneous	Sandstone, flysch	Marl, clay, conglomerates	Basic igneous	Shale, schist	Alluvium, colluvium
	2.0	1.8	1.6	1.3	1.4	1.2	1.0
Rock fragments on soil surface (%)	<15	15–40	40–80	>80			
	2.0	1.0	1.6	1.8			
Slope aspect	N, NW, NE	S, SW, SE	Plain				
	1.0	2.0	1.0				

Table 2 continued

Soils								
Slope gradient (%)	<2	2–6	6–12	12–18	18–25	25–35	35–60	>60
	1.0	1.2	1.4	1.6	1.7	1.8	1.9	2.0
Soil depth (cm)	<15	15–30	30–60	60–100	100–150	>150		
	2.0	1.8	1.6	1.4	1.2	1.0		
Soil textural class	Very coarse	Coarse	Medium	Moderate fine	Fine	Very fine		
	2.0	1.8	1.6	1.2	1.3	1.4		
Soil water storage capacity (mm)	<50	50–100	100–200	200–300	>300			
	2.0	1.8	1.5	1.3	1.0			
Exposure of rock outcrops (%)	None	2–10	10–30	30–60	>60			
	1.0	1.3	1.5	1.8	2.0			
Organic matter of surface horizon (%)	High (>6.0)	Medium (2.1–6.0)	Low (2.0–1.1)	Very low (<1.0)				
	1.0	1.3	1.6	2.0				
Degree of soil erosion	None	Slight	Moderate	Severe	Very severe			
	1.0	1.2	1.5	1.8	2.0			
Electrical conductivity (dS m^{-1})	Free, (EC < 2)	Slight (EC = 2–4)	Moderate (EC = 4–8)	High (EC = 8–15)	Very high (EC > 15)			
	1.0	1.3	1.5	1.8	2.0			
Vegetation								
Major land use	Agriculture	Pasture	Shrub land	Forest	Mining	Recreation		
	1.5	1.6	1.4	1.0	2.0	1.2		
Agricultural cover type	Cereals	Olives	Vines	Almonds	Oranges	Vegetables	Cotton	Bare land
	2.0	1.0	1.4	1.3	*1.6*	*1.8*	*1.5*	*2.0*
Natural vegetation cover type	Mixed Mediterranean machia/evergreen forest	Mediterranean machia	Permanent grassland	Annual grassland	Deciduous forest	Pine forest	Evergreen forest	Bare land
	1.2	1.4	1.5	1.8	*1.6*	*1.4*	*1.0*	*2.0*
Plant cover (%)	<10	10–25	25–50	50–75	>75			
	2.0	1.8	1.5	1.3	*1.0*			
Deforested area (% $year^{-1}$)	Low (<1.5)	Moderate (1.5–2.5)	High (2.5–3.50)	Very high (>3.5)				
	1.0	1.3	1.7	2.0				

Table 2 continued

Water runoff							
Drainage density (km of channels km^{-2})	Coarse (<5)	Medium (5–10)	Fine (10–20)	Very fine (>20)			
	1.0	1.3	1.7	*2.0*			
Flooding frequency	No	Very rare (once/10 years)	Rare (once/6–10 years)	Infrequent (once/3-5 years)	Frequent (once/1-2 years)		
	1.0	1.2	1.5	*1.7*	*2.0*		
Impervious surface area (ha 10 km^{-2} of territorial 10 years^{-1})	Low (<10)	Moderate (10–25)	High (26–50)	Very high(>50)			
	1.0	1.3	1.7	*2.0*			
Fires							
Fire frequency (years)	Low (once/>50)	Moderate (once/25–50)	High (once/25–15)	Very high (once/ <15)			
	1.0	1.3	1.7	*2.0*			
Fire risk	Low	Moderate	High	Very high			
	1.0	1.4	1.7	*2.0*			
Burned area (ha burned 10 years^{-1} 10 km^{-2} of territorial)	Low (<10)	Moderate (10–25)	High (26–50)	Very high (>50)			
	1.0	1.3	1.7	*2.0*			
Agriculture							
Farm ownership	Owner-farmed	Tenant-farmed	Shared-farmed	State-farmed	Other		
	1.0	2.0	1.5	1.7			
Farm size (ha)	<2	2–5	5–10	10–30	30–50	50–100	>100
	2.0	1.8	1.6	1.5	1.3	1.1	1.0
Land fragmentation (No. of parcels)	1–3	4–6	7–9	10–12	13–15	16–19	>19
	1.0	1.2	1.4	1.6	1.8	1.9	2.0
Net farm income	Low (<Local mean—St. Dev.)	Moderate (>Local mean—St. Dev. < local mean)	High (>Local Mean < Local Mean + St. Dev.)	Very high (>Local Mean + St. Dev.)			
	2.0	1.7	1.3	1.0			
Parallel employment	No	Industry	Tourism	State	Municipality		
	1.0	2.0	1.4	1.7	1.5		
Cultivation							
Tillage operations	No	Plowing	Disking, harrowing	Cultivator			
	1.0	2.0	1.7	1.4			
Frequency of tillage (number)	No	1	2	3	4		
	1.0	1.2	1.4	1.7	2.0		

Table 2 continued

Cultivation							
Tillage depth (cm)	No	<20	20–30	30–40	>40		
	1.0	1.1	1.3	1.7	2.0		
Tillage direction	Down-slope	Up-slope	Parallel to Contour up-slope furrow	Parallel to Contour down-slope furrow	Down-slope Oblique	Up-slope Oblique	Other (No tillage)
	2.0	1.4	1.2	1.5	1.8	1.3	1.0
Mechanization index	Low (<Local mean—St. Dev.)	Moderate (>Local mean—St. Dev. < local mean)	High (>Local Mean < Local Mean + St. Dev.)	Very high (>Local Mean + St. Dev.)			
	1.0	1.3	1.7	2.0			
Husbandry							
Grazing control	No	Sustainable Number of animal	Fencing	Avoidance of soil compaction (very wet soil)	Fire Protection		
	2.0	1.0	1.2	1.4	1.3		
Grazing intensity	Low (SR < GC)	Moderate (SR = GC to 1.5GC)	High (SR > 1.5GC)				
	1.0	1.5	2.0				
Land management							
Fire protection (Protected/total area, %)	No	Low (<25)	Moderate (25–50)	High (50–75)	Very high (>75)		
	2.0	1.8	1.6	1.3	1.0		
Sustainable farming	No sustainable farming	No tillage	Minimum tillage	Inducing plant cover	Up-slope tillage	Minimum plowing depth	
	2.0	1.0	1.3	1.1	1.4	1.5	
Reclamation of affected areas	No	Adequate drainage	Adequate salt leaching	Adequate liming of acid soils	Low heavy metal concentration		
	2.0	1.0	1.0	1.0	1.0		
Reclamation of mining areas (area protected/total area, %)	No	Low (<25 % protected)	Moderate (25–75 % protected)	Adequate (>75 % protected)			
	2.0	1.7	1.3	1.0			
Soil erosion control measures (area protected/total area, %)	No	Low (<25 % protected)	Moderate (25–75 % protected)	Adequate(>75 % protected)			
	2.0	1.7	1.4	1.0			
Soil water conservation measures	Weed control	Mulching	Temporary storage of water runoff	Inducing vapor adsorption	No		
	1.0	1.0	1.0	1.2	2.0		

Table 2 continued

Land management								
Terracing (presence of) (area protected/total area, %)	No	Low (<25)	Moderate (25–50)	High (50–75)	Very high (>75)			
	2.0	1.7	1.5	1.2	1.0			
Land use								
Land abandonment (ha 10 years^{-1} 10 km^{-2})	Low (<10)	Moderate (10–25)	High (26–50)	Very high (>50)				
	1.0	1.3	1.6	2.0				
Land use intensity	Low	Medium	High					
	1.0	1.5	2.0					
(Period) of existing land use (years)	<1	1–5	5–10	10–20	30–50	>50		
	2.0	1.8	1.6	1.4	1.2	1.0		
Distance from seashore (km)	<0.25	0.25–0.5	0.5–1	1–2	2–5	5–8	8–15	>15
	2.0	1.9	1.7	1.5	1.3	1.2	1.1	1.0
Water use								
Irrigation percentage of arable land	<5	5–10	10–25	25–50	>50			
	2.0	1.8	1.6	1.3	1.0			
Runoff water storage	No	Low	Moderate	Adequate				
	2.0	1.8	1.4	1.0				
Water consumption per sector (% per year)	Industry	Tourism	Domestic	Irrigation				
	2.0	1.6	1.8	1.0				
Water scarcity (Water available per capita/water consumption per capita in last 10 years = R)	No ($R > 2$)	Low ($R = 1.5$–2)	Moderate ($R = 1$–1.5)	High ($R = 0.5$–1)	Very high ($R < 0.5$)			
	1.0	1.2	1.4	1.7	2.0			
Tourism								
Tourism intensity (number of overnight stays 10 km^{-2} = R)	Low ($R < 0.01$)	Moderate ($R = 0.01$–0.04)	High ($R = 0.04$–0.08)	Very high ($R > 0.08$)				
	1.0	1.3	1.7	2.0				
Tourism change (Number of overnight stays in a specific destination in one year average overnight stays in the last 10 years = R, %)	Low ($R < 2$)	Moderate ($R = 2$–5)	High ($R = 5$–10)	Very high ($R > 10$)				
	1.0	1.3	1.7	2.0				

Table 2 continued

Social				
Human poverty index (HPI) (%)	Low (HPI < 10)	Moderate (HPI = 10–20	High (HPI = 20–50)	Very high (HPI = $R > 50$)
	1.0	1.3	1.7	2.0
Old age index (population with age > 65/total population = R, %)	Low ($R < 5$)	Moderate (R = 5–10)	High (R = 10–20)	Very high ($R > 20$)
	1.0	1.3	1.7	2.0
Population density (people km^{-2})	Low (<50)	Moderate (50–100)	High (100–300)	Very high (>300)
	1.0	1.3	1.7	2.0
Population growth rate (% $year^{-1}$)	Low (<0.2)	Moderate (0.2–0.4)	High (0.4–0.6)	Very high (>0.6)
	1.0	1.3	1.7	2.0
Population distribution (urban population/rural population, %)	>20	10–20	5–10	<5
	1.0	1.3	1.7	2.0

Institutional							
Subsidies	No	Subsidies/environmental protection	Subsidies/area	Subsidies/number of animals	Subsidies/kg of production		
	1.2	1.0	2.0	2.0	2.0		
Protected areas	No	Nature reserves/ wilderness	National park	National monument	Habitat/species management	Protected landscape	Managed resource
	1.5	1.0	1.0	1.0	1.3	1.2	1.0
Policy implementation	Adequate >75 % of the area	Moderate (25–75 % of the area)	Low (<25 % of the area)	No			
	1.0	1.4	1.7	2.0			

Table 3 Desertification risk classes with the corresponding description

A/A	Desertification risk class	Description
1	Very high risk	Critical areas to desertification highly degraded and subjected to very high erosion rates due to intensive cultivation, overgrazing, frequent fires; or to very high salinization rates due to the presence of shallow groundwater table or irrigation with poor quality of water
2	High risk	Critical areas to desertification highly degraded subjected to moderate or slight erosion rates or fragile areas to desertification moderately degraded subjected to very high erosion rates due to intensive cultivation, overgrazing, frequent fires; or to high salinization rates due to the presence of moderately shallow groundwater table or irrigation with poor quality of water
3	Moderate risk	Fragile areas to desertification moderately degraded subjected to high or moderate erosion rates or potential areas to desertification subjected to very high or high erosion rates due to intensive cultivation, overgrazing, frequent fires; or to moderate salinization rates due to the presence of moderately deep groundwater table or irrigation with moderate quality of water
4	Low risk	Fragile areas to desertification moderately degraded subjected to low erosion rates or potential areas to desertification slightly degraded subjected to moderate erosion rates due to intensive cultivation, overgrazing, frequent fires; or to low salinization rates due to the presence of relatively deep groundwater table or irrigation with moderately good quality of water
5	No risk	Potential or non-threatened areas to desertification slightly or no degraded subjected to very low or no erosion; or fragile, potential, non-threatened areas to desertification subjected to no salinization risk due to the presence of very deep ground water table or irrigation with good quality of water

Fig. 1 Distribution of the investigated study sites

thematicmenu-173/160-manual-for-describing-land-degradation-indicators).

Data were collected at the scale of field site. Cultivated fields with an area usually ranging from 0.5 to 20 ha, and having uniform soil, topography, land use, and land management characteristics were considered as a single sampling point (Fig. 2). Some points were identified from topographic maps or ortho-photo maps in grids of 400 m by 400 m applying a systematic sampling design. However, this approach was not easily applied because the presence of the land owner was necessary for the collection of some data related to land management and social characteristics. Therefore, the majority of the sampling points were described after contacting the owner of the land. The location of each sampling point was pin-pointed using a GPS. The datasets collected for the various indicators and processes were included in a harmonized database for further analysis. A minimum number of 30 sampling points were studied for each land degradation process for most of the study sites.

The statistical analysis was conducted using STATISTICA (www.statsoft.com). All data were classified according to land degradation processes or causes and land-uses and a harmonized data base was formed. The database was checked for missing values which were filled by calculating the mean of adjacent sampling point. The

Fig. 2 Example of study field site (sampling point) with defined soil, topography, land use, and land management characteristics belonging to a certain farmer

number of candidate indicators used for the analysis in each process or cause ranged from 16 to 50. A forward stepwise multiple regression analysis was applied using desertification risk as the dependent variable and the candidate indicators assigned for each process as independent variables, using the following linear model (Steel and others 1997):

$$\Upsilon = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_\kappa X_\kappa$$

where Y is the dependent variable of desertification risk, β_0 is the Y intercept, β_1, β_2, etc. are slopes of the regression plane, and X_1, X_2, etc. are the independent variables of the indicators used. A linear model was chosen because this is the simplest form, and because there is no evidence that a linear model is not suitable. A 95 % confidence interval was used for the regression analysis. An analysis of covariance was made for every possible pair of indicators. The selection of pairs of indicators with significant covariance was made using the correlation matrix by considering only values >0.75 (significance level set at $a = 0.05$). For each pair of indicators that proved to be highly correlated, one of them was excluded from the analysis.

Assessment of the Derived Methodology

The methodology for defining land degradation and desertification risk was verified using independent indicators measured in sampling points located in Greece that were not used for model development. The validation was conducted only for the process of soil erosion in cropland and pastures. The assessment was based on the comparison of the desertification risk index (DRI) with: (a) existing experimental soil erosion data, and (b) data for soil organic matter content of the surface horizon. Soil organic matter content clearly affects soil aggregate stability and soil erosion.

Soil erosion data were collected by the Agricultural University of Athens in the framework of the following European Commission research projects: (a) Mediterranean Desertification and Land Use-MEDALUS I (Kosmas and others 1993), (b) MEDALUS II (Kosmas and others 1995; Moustakas and others 1995; Danalatos and others 1995; Tsara and others 2001), and (c) Tillage Erosion: Current State, Future Trends and Prevention–TERON (Kosmas and others 2001; Gerontidis and others 2001). The data were collected at nine experimental sampling points under various soil, topographic, land-use, and climatic conditions. The soil losses measured during rainfall events were expressed on annual average basis for comparison with land DRI defined by the methodology described in this paper.

Concerning soil organic matter content, 39 sampling points were selected in the study site of Crete. The sampling points were located in soils formed in various parent materials, under various climatic, topographic, and land-use types. In each sampling point, all the necessary indicators for defining desertification risk were measured. Soil samples were taken from the surface A-horizon for laboratory analysis. The selected soil samples were analyzed for organic carbon content using the modified Walkey-Black wet oxidation procedure (Nelson and Sommers 1996).

Results and Discussion

Methodology for Assessing Desertification Risk

The complete list of candidate indicators, even though directly or indirectly related to land degradation and desertification, was too large to be practically applicable. The list was substantially reduced after the statistical analysis to include only the most appropriate and effective indicators suited to the range of local physical and socio-economic conditions of the sampling points. Only those indicators that entered the regression equations and that did not have very high covariance with other indicators were retained. Table 4 shows the number of effective indicators retained for each degradation process compared with the original candidates.

The analysis of the indicators for the various processes or causes has shown that a single indicator cannot effectively assess the risk of land degradation and desertification. The effects on the state parameters are usually complex and interdependent and may have differing effects depending on the state indicators. Therefore, a combination of indicators is necessary to assess the risk of land

Table 4 Number of candidate indicators used for the analysis and number of effective indicators for each process or cause of land degradation and desertification

a/a	Degradation process	Major land use	Number of candidate indicators	Number of effective indicators
1	Soil erosion by water runoff	Agriculture	49	17
		Pastures and shrubland	49	15
		Forests	49	11
2	Tillage erosion	Agriculture	16	10
3	Soil salinization	Agriculture, natural vegetation	29	9
4	Water stress	Agriculture, natural vegetation	50	12
5	Overgrazing	Natural vegetation, agriculture	44	16
6	Forest fires	Natural vegetation	30	8

desertification related to the physical environment, socio-economic conditions and land management characteristics. However, the results of the analysis of a wide range of possible candidates show that in practice fewer "effective" indicators are needed making data collection more feasible.

Table 5 gives the significant beta values of the stepwise linear regression for each indicator and process for the algorithms assessing land degradation and desertification risk. The majority of indicators defining desertification risk were related to a combination of the physical environment (climate, soil, water, vegetation), land management, social and economic characteristics of the sampling points.

The statistical analyses have shown that the greatest number of effective indicators affecting land desertification risk was defined for agricultural areas (17 indicators) with water erosion as the main process of land degradation, and in pastures (16 indicators) with overgrazing as the main cause of land degradation (Table 4). Furthermore, the lowest number of effective indicators for assessing land desertification has been identified for agricultural areas located mainly in plains (9 indicators) with soil salinization as the main process of land degradation, and for forested areas (8 indicators) with forest fires as the main cause of land degradation. The most important indicators affecting land desertification risk in the various land uses (beta values of linear regression >0.2) with the corresponding land degradation processes or causes of land degradation are the following (Table 5):

- Agricultural areas—water erosion: annual rainfall, rainfall seasonality, slope gradient, rate of land abandonment, land use intensity, and policy implementation of existing regulations on environmental protection.
- Pastures—water erosion: rainfall seasonality, percentage of plant cover, tillage depth, farm subsidies, and policy implementation.
- Forested areas—water erosion: rainfall seasonality, aridity index, soil depth, vegetation cover type, fire risk, rate of burned area, fire protection, and population density.
- Agricultural areas—tillage erosion: parent material, slope gradient, organic matter content in the soil surface, tillage operations, tillage depth, and land use intensity.
- Agricultural areas—soil salinization: annual potential evapotranspiration (ETo), water quality, rate of ground water exploitation, soil drainage, flooding frequency, distance from seashore, irrigation percentage of arable land, and population density.
- Agricultural or natural areas—water stress: rainfall seasonality, rate of land abandonment, tourism change, and policy implementation.
- Pastures—overgrazing: rainfall seasonality, rainfall erosivity, aridity index, soil drainage, percentage of plant cover, fire frequency, rate of burned area, parallel employment, grazing intensity, fire protection, soil erosion control, rate of land abandonment, period of existing land use.
- Natural areas—forest fires: rainfall seasonality, major land use, grazing control.

Rainfall seasonality has been identified as the most important indicator affecting land desertification risk in areas with the following processes or causes of land degradation: water erosion, water stress, overgrazing, and forest fires. Based on the existing literature on using indicators for assessing land desertification, vegetation cover has been reported in many studies especially in assessing land desertification by remote sensing techniques (Rubio and Bochet 1998; Kosmas 2003; Symeonakis 2004; Brandt and Geeson 2005; Arnab and Dipanwita 2011; Kairis and others this issue). The indicators aridity index and annual rainfall, soil depth, population density, organic matter content, rate of land abandonment have been considered as important indicators for assessing land degradation and desertification by many international organizations such as European Environmental Agency (EEA) (http://themes.eea.europa.eu/indicators), Commission on Sustainable Development (CSD) (http://www.un.org/esa/sustdev/natlinfo/indicators/isd.htm), United Nations Environment Programme (UNEP), as well as for compiling National Action Plans for Combating Desertification in the frame of the United Nations Convention to Combat Desertification (UNCCD) (http://www.unccd.int/). In addition, the indicators slope gradient, land use intensity, policy implementation, rate of burned area, parent material, water quality, soil drainage, grazing intensity, major land use have been reported in studies for defining land desertification (Kosmas and others 1999; Enne

Table 5 Significant beta values of stepwise linear regression analysis for assessing land degradation and desertification risk in various land uses and degradation processes or causes (β values are always close to 0)

Indicators	Water erosion			Tillage erosion	Soil salinization	Water stress	Overgrazing	Forest fires
	Agricultural areas $R^2 = 0.52$	Pastures and shrub land $R^2 = 0.76$	Forests $R^2 = 0.45$	$R^2 = 0.45$	$R^2 = 0.65$	$R^2 = 0.74$	$R^2 = 0.85$	$R^2 = 0.42$
Climate								
Rainfall	0.348							
Potential ETo					0.225			
Rainfall seasonality	−0.245	0.654	0.410			0.316	0.427	0.361
Rainfall erosivity							−0.306	
Aridity index			0.225				0.541	
Water								
Water quality					0.346			
Groundwater exploitation					1.497	0.194		
Soil								
Drainage					0.413		−0.308	
Parent material				−0.206				
Slope aspect	0.191							
Slope gradient	0.359			0.429		0.194		
Soil depth	0.082	0.167	0.225					
Soil texture		0.115						
Organic matter	0.170			0.314				
Exposure of rock outcrops							0.189	
Vegetation								
Major Land use				0.159				−0.284
Vegetation cover type	0.089		0.369					
Plant cover	0.089	0.305	0.169				0.413	
Deforested area						−0.110		
Water runoff								
Flooding frequency					−0.295			
Impervious surface area						−0.107		
Fires								
Fire risk			−0.417					
Fire frequency						−0.139	0.401	
Burned area		−0.182	0.309				−0.496	
Agriculture								
Farm size							0.587	
Farm ownership					0.152			
Land fragmentation							1.581	0.106
Parallel employment	−0.159							
Cultivation								
Tillage operations	0.158			0.320				
Tillage depth		−0.240		0.207				
Tillage direction		0.124						
Mechanization index				−0.164				
Husbandry								
Grazing control		0.186					0.179	0.616
Grazing intensity			−0.392				0.256	
Land management								
Fire protection			0.247				0.941	0.167

Table 5 continued

Indicators	Water erosion			Tillage erosion	Soil salinization	Water stress	Overgrazing	Forest fires
	Agricultural areas $R^2 = 0.52$	Pastures and shrub land $R^2 = 0.76$	Forests $R^2 = 0.45$	$R^2 = 0.45$	$R^2 = 0.65$	$R^2 = 0.74$	$R^2 = 0.85$	$R^2 = 0.42$
Sustainable farming	0.196							
Soil erosion control						0.194	0.435	
Soil water conservation		0.134						
Terracing (presence)	0.176			0.107				
Land use								
Land abandonment	−0.364		0.133			−0.442	−0.971	
Land use intensity	0.205	0.175		0.368				0.120
Period of existing land use		0.112					−0.221	
Distance from seashore					0.297			
Water use								
Irrig. % of arable land					0.836			
Runoff water storage	−0.155	0.314						
Water scarcity						0.028		
Tourism								
Tourism intensity		0.127						
Tourism change						0.313		
Population								
Old age index								0.117
Population density			0.356		−0.573	0.108		
Population growth rate								−0.111
Institutional								
Farm subsidies	0.105	0.405						
Policy implementation	0.380	0.282		0.116		1.096		

and Zucca 2000; Basso and others 2012; Kairis and others this issue).

The following is an example of the algorithm derived for assessing DRI in areas where the main process of land degradation is water stress:

$$\begin{aligned}\mathrm{DRI} &= 0.316 \times \mathrm{RS} + 0.194 \times \mathrm{GE} + 0.194 \\ &\quad \times \mathrm{SG} - 0.110 \times \mathrm{DA} - 0.107 \times \mathrm{IS} - 0.139 \times \mathrm{FR} \\ &\quad + 0.194 \times \mathrm{SEC} - 0.442 \times \mathrm{RLA} + 0.028 \times \mathrm{WS} \\ &\quad + 0.313 \times \mathrm{TC} + 0.108 \times \mathrm{PD} + 1.096 \times \mathrm{PI}.\end{aligned}$$

where RS is the rain seasonality, GE is the rate of ground water exploitation, SG is the slope gradient (%), DA is the rate of deforested area (% year^{-1}), IS is the rate of impervious surface area cover (ha 10 km^{-2} of territorial surface 10 years^{-1}), FR is the fire frequency (years), SEC is the soil erosion control (area protected per total area, %), RLA is the rate of land abandonment (ha 10 years^{-1} 10 km^{-2}), WS is the water scarcity (water available supply per capita/water consumption per capita during the last 10 years), TC is the tourism change (number of overnight stays in a specific destination over 1 year/average overnight stays in the last 10 years, %), PD is the population density (people km^{-2}), PI is the policy implementation of existing regulations for environmental protection.

As an example of its application, the following sampling point used as grazing land in Fig. 3 is given. The land belongs to two farmers separated by a fence. The left side is overgrazed, while the right part is sustainable grazed. Climate, topography, soil, and vegetation type characteristics are the same in both points. By introducing all the appropriate indicators in the derived methodology for pastures (Table 5), the estimated DRI for the left side is 5.4 (very high), while the DRI for the right side is only 4.4 (high). All the desertification processes and the indicators that can be used to assess these processes are described in detail by Kairis and others (this issue).

The developed methodology is an important decision support tool that can be used by various stakeholders for assessing land degradation and desertification risk in any geographical area subjected to land degradation and desertification. It is a tool for selecting the appropriate land

Fig. 3 Grazing land belonging to two farmers and subjected to grazing intensity

management practices and techniques for combating desertification. The proposed methodology provides a series of effective indicators that would help people to identify where land desertification is a current or potential problem, and which could be the actions to alleviate the problem over time. For the application the following steps must be followed: (a) choose the appropriate land use (agriculture, pasture, forest) (Table 4), (b) decide for the land degradation process or cause (water erosion, tillage erosion, sol salinization, etc.) for selecting the appropriate equation (Table 5), (c) define the data and the appropriate indices of the corresponding indicators (Table 2) and introduce to the equation, and (d) calculate the DRI. The derived methodology can be easily used through the expert system loaded in the DESIRE website available at: http://www.desire-his.eu/en/assessment-with-indicators/wp22-evaluation-a-short-list-of-indicators-thematicmenu-174/66-study-site-indicators. After defining desertification risk, the land user has the ability to change values of indicators related to land use and land management practice for establishing promising conservation strategies for reducing desertification risk at field or regional level. As described by Karavitis and others (this issue) a computer application has been developed that allows users to calculate desertification risk based on the equations that have been developed.

Methodology Assessment

This methodology for defining land degradation and desertification risk (DRI) was assessed using independent data on erosion and soil organic matter content, that were collected in the study sites of Greece. Soil erosion is one of the most important processes of land degradation and desertification particularly affecting sloping areas. Figure 4 shows a significant correlation between measured soil erosion data and the calculated DRI ($R^2 = 0.63$). DRI increases rapidly for low rates of soil erosion (up to 5 t ha^{-1} year^{-1}) and then more slowly when erosion rates are very high. The relationship observed in the upper horizontal part of the curve can indicate the resilience of a system to withstand desertification. For example a relatively deep soil under certain climatic, vegetative, and topographic conditions characterized with moderate DRI will remain moderate until soil depth reaches a threshold value (<30 cm) where desertification risk is high with low potential of the ecosystem to continue providing services. The results show that applying the indicator methodology is indeed a good tool to assess the risk for land desertification in the case where soil erosion is the main process of land degradation.

Soil organic matter is a key indicator for soil quality, both for agricultural and environmental functions. Soil organic matter is a major indicator influencing physical, chemical, and biological soil variables. Aggregation and stability of soil structure increases with organic matter content (Tisdall and Oades1982; Milne and Haynes 2004). This in turn increases infiltration rate and available water capacity of the soil, as well as resistance to erosion by water and wind (Bissonnais and Arrouays 1997). Decrease of organic matter content is a key factor in accelerating soil erosion and irreversible land degradation and desertification.

As Fig. 5 shows, DRI decreases as soil organic matter content in the surface horizon increases. The correlation coefficient is not so high ($R^2 = 0.32$; $P < 0.05$; df = 37) since other factors such as land management practices, climatic conditions, and soil characteristics may overrule the positive effect of soil organic matter content. Nevertheless, these validation data indicate that the developed indices were performing well for Greece. Of course, this limited validation with data from Greece only does not provide proof that the method performs well around the world. Hence, the availability of reliable and accurate pertinent data from other field sites around the world would enhance the assessment effort. However, the applicability

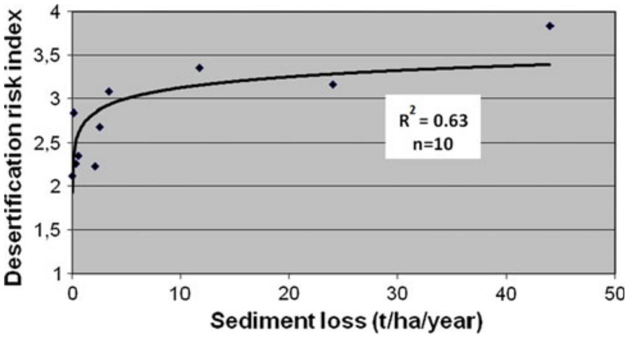

Fig. 4 Measured soil loss and desertification risk index as calculated with equations shown in Table 5

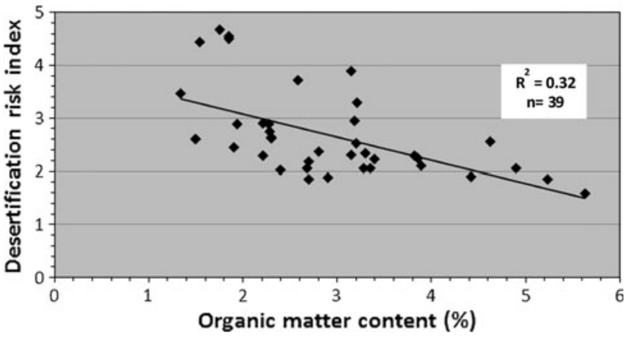

Fig. 5 Relation of desertification risk index estimated by the derived methodology and organic matter content of the surface horizon measured for the same sites

of the proposed methodology is partially validated by the identification of the most important indicators related to the degradation processes of water erosion in various land uses, tillage erosion, soil salinization, water stress, and causes of forest fires, and overgrazing in 17 study sites located in a variety of physical environment, social, and economic conditions (Kairis and others this issue).

Conclusions

This study demonstrates that a careful selection of indicators may be used to assess desertification risk in areas prone to this type of land degradation. Desertification risk can be assessed using both indicators related to the biophysical environment which cannot be easily altered and to land management practices or agricultural and institutional characteristics that are related to human actions. This study indicates that there are relatively few important indicators for each process or cause of land degradation related to human actions which can be changed to reduce desertification risk. The comparison of land degradation and desertification risk with independent indicators measured in the study site of Crete showed clear relationships, indicating that these indicators may be used to assess desertification risk.

The equations that were developed were based on data obtained from 17 study sites around the world, each with their own bio-physical, socio-economic, and political conditions. The fact that single equations could be developed based on data from these diverse sites provides some indication that the method developed could be applied worldwide. No major difficulties were encountered when the method was applied in the DESIRE study sites; although some minor improvements were suggested, especially in the classes assigned to some indicators, to make the method more easily applicable outside the Mediterranean area.

Acknowledgments The research described in this paper was conducted within the framework of the EC-DG RTD, 6th Framework Research Programme (sub-priority 1.1.6.3), Research on Desertification, project DESIRE (037046): Desertification Mitigation and Remediation of Land—a global approach for local solutions. The financial support by the European Commission is gratefully acknowledged.

References

Allen H, Adriaanse A, Rodenburg E, Bryant D, Woodward R (1995) Environmental Indicators. World Resources Institute, Washington, D.C., p 49

Arnab K, Dipanwita D (2011) Monitoring desertification risk through climate change and human interference using remote sensing and GIS techniques. Int J Geomat Geosci 2(1):21–33

Basso B, De Simone L, Cammarano D, Martin EC, Margiotta S, Grace PR, Yeh ML, Chou TY (2012) Evaluating responses to land degradation mitigation measures in Southern Italy. Int J Environ Resour 6(2):367–380

Benabderrahmane M, Chenchouni H (2010) Assessing environmental sensitivity areas to desertification in Eastern Algeria using Mediterranean desertification and land use "MEDALUS" model. Int J Sustain Water Environ Syst 1(1):5–10

Brandt J, Geeson N (2005) Desertification Information System to Support National Action Programmes in the Mediterranean (DISMED). DIS4ME, Desertification Indicator System for Mediterranean Europe. www.unibas.it/desertnet/dis4me/. Accessed 20 Feb 2012

COP9 (2009) Advice on how best to measure progress on strategic objectives 1, 2 and 3 of the strategy. Decision 17/COP.9. http://www.unccd.int/. Accessed 30 June 2011

Danalatos NG, Kosmas C, Moustakas N, Yassoglou N (1995) Rock fragments II: their impact on soil physical properties and biomass production under Mediterranean conditions. Soil Use Manage 11:121–126

Dregne H, Kassas M, Rozanov B (1991) A new assessment of the world status of desertification, UNEP. Desertification Control Bull 20:6–18

EEA (2005) Technical report EEA core set of indicators, Guide/No1/2005

Enne G, Zucca C (2000) Desertification indicators for the European Mediterranean region: state of the art and possible methodological approaches. ANPA, Roma and NRD, Sassari, p 261

Finke P, Hartwich R, Dudal R, Ibanez J, Jamagne M, King D, Montanarella L, Yassoglou N (1998) Georeferenced soil database for Europe, Manual of procedures, version 1. European Soil Bureau, Scientific Committee

Gerontidis St, Kosmas C, Detsis V, Marathianou M, Zafiriou Th, Tsara M (2001) The effect of moldboard plough on tillage erosion along a hillslope. Soil Water Conserv J 56:147–152

Imeson AC (1996) Desertification research—Thematic issues and spatial and temporal scaling. In: Hill J, Peter D (eds) The use of remote sensing for land degradation and desertification monitoring in the Mediterranean basin. European Commission, Brussels

Kosmas C, Yassoglou N, Kallianou Ch, Danalatos N, Moustakas N, Tsatiris B (1993) Field site investigation: Spata. Athens, Greece. In: Mediterranean desertification and land use—MEDALUS I final report. Commission of the European Communities. Contract Number EPOC-CT90-0014-(SMA), p 581–607

Kosmas C, Yassoglou N, Moustakas N, Danalatos N (1995) Field site: Spata, Greece. In: Mediterranean desertification and land use—MEDALUS II final report. Basic Field Programme. Commission of the European Communities. Contract Number EV5V-CT92-0128, p 129–163

Kosmas C, Kirkby M, Geeson N (1999) Manual on: key indicators of desertification and mapping environmentally sensitive areas to desertification. European Commission, Energy, Environment and Sustainable Development, EUR 18882, p 87

Kosmas C, Danalatos NG, Gerontidis St (2000a) The effect of land parameters on vegetation performance and degree of erosion under Mediterranean conditions. Catena 40:3–17

Kosmas C, Gerontidis St, Marathianou M (2000b) The effect of land use change on soil and vegetation over various lithological formations on Lesvos. Catena 40:51–68

Kosmas C, Gerontidis St, Marathianou M, Detsis V, Zafiriou Th (2001) The effect of tillage erosion on soil properties and cereal biomass production. Soil Tillage Res J 58:31–44

Kosmas C, Tsara M, Moustakas N, Karavitis C (2003) Identification of indicators for desertification. Ann Arid Zone 42:393–416

Le Bissonnais Y, Arrouays D (1997) Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic carbon contents. Eur J Soil Sci 48:39–48

Liniger H, Schwilch G, Gurtner M, Mekdaschi Studer R, van Lynden G, Critchley W (2007) Word Overview of Conservation Approaches and Technologies. A Framework for Documentation and Evaluation of Land Conservation, http://www.wocat.org/. Accessed 12 Oct 2011

Milne RM, Haynes RJ (2004) Soil organic matter, microbial properties, and aggregate stability under annual and perennial pastures. Biol Fertil Soils 39:172–178

Moustakas NC, Kosmas CS, Danalatos NG, Yassoglou N (1995) Rock fragments I. Their effect on runoff erosion and soil properties under field conditions. Soil Use Manage 11:115–120

Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. In: AL Page et al. (ed) Methods of soil analysis, part 2, 2nd ed., Agronomy, vol 9. American Society of Agronomy, Inc. Madison, pp 961–1010

OECD Key environmental indicators (2004) http://www.oecd.org/dataoecd/32/20/31558547.pdf. Accessed 20 Sept 2011

Oldeman LR (1988) Guidelines for general assessment of the status of human-induced soil degradation. Working paper 8814. ISRIC, Wageningen

Oldeman LR, Hakkeling RTA, Sombroek WG (1990) World map of the status of human-induced soil degradation. An explanatory note. ISRIC/UNEP, Wageningen

Parvari S, Pahlavanravi A, Nia A, Dehvari A, Parvari D (2011) Application of methodology for mapping environmentally sensitive areas (ESAs) to desertification in dry bed of Hamoun Wetland (Iran). Int J Nat Resour Marine Sci 1:65–80

Recatala L, Fabbri AG, Zink JA, Frances A, Sanchez I (2002) Environmental indicators for assessing and monitoring desertification and its influence on environmental quality in Mediterranean environments. In: Rubio J, Morgan RPC, Asins S, Andreu V (eds) Man and soil at the third millennium, ESSC vol 1., pp 897–910

Rubio JL, Bochet E (1998) Desertification indicators as diagnosis criteria for desertification risk assessment in Europe. J Arid Environ 39:113–120

Rubio JL, Recatala L (2006) The relevance and consequences of Mediterranean desertification including security aspects. In: Kepner WG, Rubio JL, Mouat DA, Pedrazzini F (eds) Desertification in the Mediterranean Region: a security issue. Springer, Netherlands, pp 133–165

Salvati L (2011) The spatial nexus between population growth and land degradation in a dry Mediterranean region: a rapidly changing pattern? Int J Sustain Dev World Ecol 19:81–88

Salvati L, Bajocco S (2011) Land sensitivity to desertification across Italy: past, present, and future. Appl Geogr 31:223–231

Salvati L, Zitti M, Ceccarelli T (2008) Integrating economic and ecological indicators in the assessment of desertification risk: suggestions from a case study. Appl Environ Ecol Res 6: 129–138

Sepehr A, Hassanli AM, Ekhtesasi MR, Jamali JB (2007) Quantitative assessment of application of methodology for mapping environmentally sensitive areas (ESAs) to desertification in south of Iran using MEDALUS method. Environ Monit Assess 134:243–254

Steel R, Torrie J, Dickey D (1997) Principles and procedures of statistics: a biometrical approach. WCB/McGraw-Hill, a Division of the McGraw-Hill Companies, p 666

Symeonakis E (2004) Monitoring desertification and land degradation over sub-Saharan Africa. Int J Remote Sensing 25(3):573–592

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163

Tsara M, Gerontidis St, Marathianou M, Kosmas C (2001) The long-term effect of tillage on soil displacement of hilly areas used for growing wheat in Greece. Soil Use Manage J 17:113–120

UNEP (1992) World Atlas of Desertification. United Nations Environment Programme. Edward Arnold, London

Van Engelen VWP, Wen TT (1995) Global and National Soils and Terrain Digital Databases (SOTER). Procedures Manual. International Soil Reference and Information Centre-ISRIC, Wageningen

Van Engelen VWP, Batjes NH, Dijkshoorn K, Huting J (2005) Harmonized global soil resources database (Final Report). Report 2005/06, FAO and ISRIC—World Soil Information, Wageningen

Wascher DM (ed) (2000) Agri-environmental indicators for sustainable agriculture in Europe. European Centre for Nature Conservation, Tilburg, p 240. ISBN 90-76762-02-3