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LAND VULNERABILITY EVALUATION AND CLIMATE CHANGE IMPACTS IN ANDALUCIA, SPAIN: SOIL EROSION AND CONTAMINATION

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Abstract. Two of the main desertification indices or land degradation risks in agricultural areas are soil erosion and contamination. Increased land degradation is one possible, and important, consequence of global climate change. Therefore, it is a priority to predict global environmental change impacts on these degradation risks. Land evaluation is a formal way to develop the capability to predict land degradation risks or vulnerability caused by interactive changes in land use and climate. The fundamental purpose of land evaluation is to predict the consequences of change. As a part of the ACCESS model, and by using standard land evaluation techniques, a qualitative prediction approach was developed to assess the risks of soil erosion and contamination in agricultural lands. Through this bio-physical approach, it is easy to modify parameters to create new evaluating scenarios, run the evaluation models, and observe their effects. The Andalucia Region of Spain was used as the test region for this approach, based on the current climate and two climate change scenarios. The evaluation results show that 16 % and 27 % of the Andalucian land area is at elevated risk of soil rainfall erosion and contamination, respectively; and a further 58 % and 33 % at medium risk. For the present drought scenario, the modelling approach predicts that in 59 % of land the erosion risk decreases, while for 24 % of land this vulnerability increases. These values are 40 % and 60 %, respectively, for soil contamination vulnerability. The second scenario assumes the predicted climate change for 2050 AD for the Mediterranean area. This evaluation predicts that in 18 % of land the erosion risk decreases, and increases in 47 % of land. For the contamination vulnerability the predicted values are similar to those of the first scenario. Thus, change in rainfall amount affected erosion risks strongly, but this change proved to have little direct influence on contamination vulnerability.

Keywords: computer-based land evaluation, qualitative models, decision trees, risk assessment, soil survey parameters, Mediterranean region

INTRODUCTION

The term desertification is presently used to cover land degradation processes in arid, semi-arid and dry-subhumid areas resulting from climatic variations and human activities [32]. These processes are degradation of the vegetative cover, biological degradation, physical soil degradation, water and wind erosion, salinization and contamination [18,36]. With special reference to the Mediterranean regions, soil erosion and contamination, as problems related to water quantity and quality respectively, are the most important soil desertification processes. Soil erosion *sensu stricto* is defined as detachment and transport of soil particles by a moving fluid: water or air [29]. De Ploey [15] produced, after compiling information from various sources, a soil erosion map of western Europe, indicating the areal extent of various erosion processes and phenomena. This map shows the spatial distribution of the main soil erosion processes, namely: soil erosion by water, soil erosion by wind, mass movement and badland formation, in the Mediterranean countries belonging to the European Union. Water and wind soil erosion are by far the dominant soil erosion processes in agricultural lands, although the area affected by severe wind erosion is fairly limited.

Soil contamination is considered in this paper as diffuse soil pollution by agricultural substances passing over or through the soil, and hence contaminating waters. Excess of mineral nutrients and organic pesticides seem to be the most significant potential contaminants. However, impurities in fertilizers, manures and wastes can also be important sources of pollution, especially with heavy metals. Soil agro-contamination phenomena are specially important in irrigated lands of the Mediterranean regions.

In studying land degradation processes, it is interesting to separate the status, rates and risks of land degradation. Land vulnerability or land degradation risks refers to the susceptibility of land to degradation in one or more of its ecological functions, within the constraints of its bio-physical characteristics. Attainable land vulnerability is based on natural factors controlling land degradation risks, basically site, soil and climate related factors. Similar integrated concepts are used in the land survey system of Australia [20]. When the soil use and management related factors are considered together, the term actual land vulnerability is used. Land degradation is characterized not only by long-term perspectives, but also by diffuse events and the size of the geographic areas affected. In spatial terms, the modelling of soil degradation is relatively well advanced at the local scale, e.g., process measurement site, experimental station, small catchment [21], but extrapolation to the regional scale, e.g., Andalucia, Spain, European Union, is still a major priority. This extrapolation can be made: i) by scaling-up techniques, developing a linkage between the controlling variables included in the degradation process models and information contained in spatial databases; or ii) by land evaluation techniques, combining expert knowledge of the degradation process and spatial database information [31].

Land evaluation procedures, as defined by FAO [16,17], have been applied widely to provide a rational basis for making land use decisions, based on relations between land use and land qualities [11,38]. However, these production-oriented applications can also be focused on land degradation or vulnerability predictions [13]. In this sense, it is interesting to test the applicability of land evaluation techniques for predicting land vulnerability risks. Spatial variability is also a major factor which complicates the assessment of land degradation risk. Land evaluation can be a useful prediction technique to establish risk differences between one place and another places [37].

The fundamental purpose of land evaluation is to predict the positive or negative consequences of change. Land evaluation can be a formal, structured method to develop the capability to assess land degradation risks caused, for example, by long-term changes in climatic conditions or/and agricultural systems. Although quantitative uncertainties in climate models remain, the general scientific consensus is that a significant climate change will occur during the next century. This climate change will not occur without significant impacts upon various sectors of our environment and consequently of our society [3]. Climatic changes in the Mediterranean regions will appear which will have an important impact on soil erosion and contamination. Also, land degradation has been identified as a global problem in which recurrent droughts have devastating impacts. Representative test cases can be formulated by considering regional differences, with respect to site and soil properties, and current and predicted climate conditions.

This paper reports an attempt to predict land degradation risks, along with their response to climate changes. A prediction approach has been developed making use of land evaluation techniques and focusing on soil erosion and contamination. This is a hybrid land vulnerability evaluation procedure obtained through decision trees, with branches based on qualitative data combined with branches using quantitative data. It is considered to be a system capable of evaluating the land vulnerability impact of climate change, simulating the effects of drought periods and predicted perturbations.

THE PREDICTION APPROACH

As part of the ACCESS model [24,26], a database/expert system evaluation approach was developed for assessing limitations for the use of land, or the vulnerability of land to specified agricultural degradation risks. Soil erosion and diffuse agrochemical contamination are considered separately by two program submodels. With special reference to agricultural lands, the erosion model focuses on soil loss caused by water and wind, and the contamination model on diffuse soil pollution by agricultural substances passing over or through the soil and hence contaminating water.

Physical-attainable risks are calculated considering site, soil and climate-related characteristics. Land use and management and socio-economic attributes are not considered in the present paper, although there is no reason why these should not be included in such a system. The models created were formulated and calibrated using scientific data (information), expert knowledge (experience) from specialists and land users, and the literature (knowledge), with special reference to Andalucia as a test region. The models have been developed for inclusion in spatially distributed systems. This requires easily available parameters, for application to large geographic regions [10].

These models are, in effect, automated applications which utilise the SDBm database [19], through the software capabilities of the MicroLEIS^{TM} system [12,14]. Hypothetical predictions, which consider climate changes, can also be easily formulated in order to design adaptation strategies. These 'what-if' scenario studies are critical pieces of the puzzle in the understanding of global change.

Spatial database information

The land vulnerability evaluation approach is based on two kinds of information: i) soil survey data, and ii) monthly meteorological data.

The models were initially formulated and calibrated using numerous data sets for Andalucia region [22]. Addition of representative sites corresponding to the European Union [7], and England and Wales [34] led to recalibration and revalidated of the models. The development of a spatial database capable of providing accurate, useful and timely data on land resources is a prerequisite for assessing the productive capacity of the land, of the status, rates and risks of soil degradation, and of global change [28]. To store and manipulate this large amount of rural resource data, in an efficient and systematic way, the following databases were developed: i) SDBm (soil-related information), and ii) CDB (climate-related information).

In the SDBm database [19] the following soil data sets can be stored: field descriptions of site and profile characteristics, in a coded format; standard soil analytical data and soluble salts data; and soil physical analytical data, especially with reference to infiltration and water retention. Major facilities of the SDBm include input, edit, print, selection and file creation. The system for coding information is flexible, making SDBm adaptable to specific national or local conditions Analytical results can be plotted on the screen, as XY and pie presentations, and the SDBm can be used in the English, French and Spanish languages, as an automatic soil terminology translation system. Also, the 'soil layer generator' option represents an useful interface between the SDBm and the land evaluation and geographical information systems. The CDB database stores and manipulates monthly meteorological data, with special reference to temperature and precipitation variables.

Expert knowledge capture

The land vulnerability evaluation approach, as with any land evaluation method, is subject to information and knowledge limitations. The expert knowledge is of two kinds: i) scientific knowledge of specialists and from the literature, and ii) practical experience of land users.

In the present study useful knowledge about land degradation processes was captured by questionnaires, interviews and discussions with a range of specialists, experts and land users. The expert team was composed of 48 specialists, selected from academic faculties and planning-oriented agencies, mainly in Spain and The Netherlands, and 32 land users. From the analysis of their responses, a knowledge base of rules was created. Afterwards, the results were discussed with specialists of a particular degradation focus, mainly from the IRNAS, and together with them the decision trees were built. Besides the personal contacts, scientific literature was an important source of information and knowledge from which to build the models, such as Wishmeier and Smith [39], Barth and L'Hermite [5], CORINE [8], Batjes and Bridges [4], McGrath and Loveland [25],. and Bouma *et al.* [6].

Following this, the models were recalibrated and validated by point-to-point application using data for Andalucia region and the European Union. In addition, the models were applied spatially for the Province of Sevilla (14,036 km^2), Spain, interpolated point data, needed to drive the models, being derived by kriging [9].

Characteristics, qualities and decision trees

The prediction approach was partly constructed in accordance with the criteria of the FAO framework for Land Evaluation [16]. However, characteristics and qualities are considered in an environmental sense. Biophysical variables are considered to be land-related characteristics, in order to calculate the attainable degradation risks. Table 1 shows the list of land characteristics as input variables of the models. For each vulnerability type, the land evaluation procedure followed is based on decision trees rather than matching tables. The decision trees, as for example shown in Table 2, are hierarchical multiway keys, in which the leaves are choice classes/ranges such as LQ ratings, and the interior nodes of the tree are decision criteria such as LC values. Through the decision trees, the qualities are associated to the characteristics, and the final decision or vulnerability classes are derived from the qualities (Table 3). Each LQ separates into four severity levels.

These empirical knowledge-based models also combine a simple precipitation partitioning sub-model to calculate the LQ's surface runoff and leaching degree, by using the humidity index as the relationship between yearly amounts of precipitation and of potential evapotranspiration. Finally, the land vulnerability classes established for each type of degradation were defined. Besides classes, subclasses are also presented as evaluation output limitations, by using the lower letter of the land and management qualities (Table 3). The meaning of the subclasses is to show the user which is the vulnerability of the evaluated field-unit and to support understanding of the evaluated classification.

The erosion model rules

Water erosion is a two phase process consisting of the detachment of individual particles from the soil mass and their transport by water. When sufficient energy is no longer available to transport the particles a third phase, deposition, occurs [27]. The classification of the attainable water erosion vulnerability is based on three LQ's: relief, soil erodibility and rainfall erosivity. Relief represents erosion which would normally be expected to increase with increased angle of slope and slope length, as a result of increases in velocity and volume of surface run-off. Further, whilst on a flat surface raindrops splash soil particles randomly in all directions, on sloping ground more soil is splashed downslope than upslope, the proportion increasing as the slope steepens. This LQ is formed by a combination of two LC's: landform (physiographical position) and slope gradient.

Soil erodibility represents the susceptibility or resistance of the soil to both detachment and transport. Although soil resistance to erosion depends in part of the topographic position, slope angle and the amount of disturbance created by man, for example during tillage, the properties of the soil profile are the most important determinants. Erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical content. This LQ is formed by the following five LC's: particle size distribution, superficial stoniness, organic matter content, surface drainage and sodium saturation percentage.

Table 1. Input variable list of the land vulnerability modelling approach

Land characteristic, class or unit	Erosion model	Contamination model
Site - related characteristics		
LC Landforms, 21 classes	xxx	xxx
LC Slope gradient, %	xxx	xxx
LC Groundwater table depth, m	xxx	xxx
Soil - related characteristics		
LC Drainage, 7 classes	xxx	xxx
LC Particle size distribution, 23 classes	xxx	xxx
LC Superficial stoniness, %	xxx	
LC Organic matter, %	xxx	xxx
LC pH		xxx
LC Cation exchange capacity, meq/100 g		xxx
LC Sodium saturation, %	xxx	
Climate - related characteristics		
LC Mean monthly precipitation, mm	xxx	xxx
LC Max monthly precipitation, mm	xxx	
LC Mean montly temperature, °C	xxx	xxx
LC Latitude, °	xxx	xxx

Table 2. Pathway of the decision tree constructed to relate the LQ leaching degree with the associated land characteristics

Evaluation		Severity level			
Step	Land characteristics	1	2	3	4
A	Humidity index	> B	> C	> D	> E
B	Ground water table depth	Low	> F	> G	
C	Ground water table depth	Low	> H	> I	
D	Ground water table depth	> J	> K	> L	
E	Ground water table depth	> M	Extr	Extr	
F	Drainage	Low	Low	> N	
G	Drainage	Mod	Mod	High	
H	Drainage	Low	> N	Mod	
I	Drainage	High	High	> O	
J	Drainage	> N	Mod	> P	
K	Drainage	> Q	High	> R	
L	Drainage	> O	Extr	Extr	
M	Drainage	High	High	Extr	
N	Particle size distribution	Low	Mod	Mod	
O	Particle size distribution	High	Extr	Extr	
P	Particle size distribution	Mod	Mod	High	
Q	Particle size distribution	Mod	High	High	
R	Particle size distribution	High	High	Extr	

Note: Under each class the symbol > followed by a letter (B to R) is used to direct the user to the next step of the decision tree. The path is followed until a severity level of the LQ is encountered. (Mod = moderate; Extr = extreme).

Table 3. Summary of environmental land qualities and associated characteristics, for each vulnerability type considered by the modelling approach

Land quality	Vulnerability type	Land characteristics
	Erosion risks model	
Relief	W	Landform; Slope gradient
Soil erodibility	W, D	Particle size distribution; Superficial stoniness; Organic matter; Drainage; Sodium saturation; Groundwater table depth.
Rainfall erosivity	W	Monthly mean precipitation; Monthly maximum precipitation; Monthly temperature; Latitude.
	Contamination risks model	
Surface erosion, r	P, N, H, X	Relief; Soil erodibility; Rainfall erosivity.
Leaching degree, l	P, N, H, X	Monthly precipitation; Monthly temperature; Latitude; Groundwater table depth; Drainage; Particle size distribution.
Phosphate fixation, f	P	pH; Particle size distribution; Organic matter.
Cation retention, c	N, H	pH; Particle size distribution; CEC; Organic matter.
Denitrification, d	N	Monthly temperature; Groundwater table depth; Organic matter; pH.
Pesticide sorption, o	X	Organic matter; pH; article size distribution; CEC.
Pesticide degradation, g	X	Monthly temperature; Monthly precipitation; pH; Organic matter.

Vulnerability types: Water (W), and Wing (D) erosion; Phosphate (P), Nitrogen (N), Heavy metal (H), and Pesticide (X) contamination.

Rainfall erosivity represents the erosivity of rainfall partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to run-off. The most commonly used rainfall erosivity index is the ratio p^2/P (Fournier index) where p is the mean monthly precipitation and P is the mean annual precipitation. It is strictly an index of the concentration of precipitation in a single month and thereby gives a crude measure of the intensity of the rainfall and of erosion protection by vegetation, in so far as a high value denotes a strongly seasonal climatic regime with a dry season during which the plant cover decays. The occurrence of a shower of rain after a dry period is especially significant for land vulnerable to soil erosion. For this reason we changed the Fournier index to the derived Fournier/Humidity erosivity index, which is derived from the monthly climate variables: mean precipitation, maximum precipitation, mean temperature using the following formula:

$$K = Sp_{\max}^2 \,/\, SP_{\max} \,/\, Hi \tag{1}$$

where, K is the derived Fournier/Humidity erosivity index, p_{max} is the highest monthly precipitation during 30 years (mm), P_{max} is the cumulative sum of the highest monthly precipitation of the 30 year period for the 12 months of the year and Hi is the Humidity index, derived using the following formula:

$$Hi = P / pET \qquad (2)$$

where, P is the annual amount of precipitation (mm), and pET is the annual amount of potential evapotranspiration (mm), calculated by the Thornthwaite method [35], such that when $Hi > 1$, then the value of Hi takes the value of 1.

The wind erosion process is the entrainment of soil particles by wind, which is effected by the application of a sufficiently large fluid force and by bombardment with soil grains already in motion [27]. The assessment owind erosion vulnerability was related only to a land quality: soil erodibility. This LQ is formed by easy available LC's, such as humidity index, particle size distribution, organic matter content and depth of the ground water level, being classified into ten severity levels.

The contamination model rules

The leaching of agricultural chemicals results from a complex interaction of physical, chemical and biological processes, and attempts have been made to model these by equations based on classical mechanistic physics, and on a statistical or stochastic framework [1]. However, models are not yet reliable enough to predict accurately the behaviour of agrochemicals in the field. Soils are heterogeneous, climate and management factors vary, both in the short and long-term, and so on. The development of land evaluation models is thus justified in terms of providing a tool with which to assess large amounts of soil information, such as that obtained from soil surveys, in order to yield the most practicable strategy for environmental protection [13]. These land vulnerability classes correspond to the potential or minimum contamination risks, considering no influence of agricultural practices. Four types of agro-contaminants are considered separately: i) phosphorus (P), ii) nitrogen (N), iii) heavy metals (H), and iv) pesticides (X).

For all the contamination risks, the transport, filtering and buffering capacities and transforming soil functions are considered by the model. A first decision tree was developed for partitioning the rainfall into two components: soil surface runoff and profile leaching regime. Table 4 shows the soil and climate related land characteristics associated to both components or land qualities.

Table 4. Monthly means of temperature and precipitation in Sevilla. Traditional climate: 1961-90; and present drought: 1990-94

Month	Temperature, °C		Precipitation, mm	
	Mean max	Mean min	Mean min	Mean max
Jan	15.8 (16.0)	5.8 (4.9)	10.8 (10.4)	89 (38)
Feb	17.5 (18.1)	6.7 (6.0)	12.1 (12.0)	73 (49)
Mar	20.3 (22.0)	8.1 (9.2)	14.2 (15.6)	54 (40)
Apr	22.4 (23.2)	9.8 (9.8)	16.1 (16.5)	57 (63)
May	26.7 (27.1)	12.4 (13.6)	19.6 (20.3)	31 (32)
Jun	31.1 (31.1)	15.8 (16.3)	23.4 (23.7)	18 (12)
Jul	35.5 (36.7)	18.3 (19.5)	26.9 (28.1)	2 (1)
Aug	35.6 (35.8)	18.2 (19.4)	26.9 (27.6)	5 (0)
Sept	32.1 (31.5)	16.9 (16.8)	24.5 (24.1)	17 (13)
Oct	26.0 (24.0)	13.3 (12.9)	19.7 (18.4)	63 (87)
Nov	19.7 (20.3)	9.2 (8.2)	14.5 (14.2)	96 (32)
Dec	16.1 (16.6)	6.4 (6.8)	11.2 (11.7)	90 (25)
Annual	24.9 (25.2)	11.7 (11.9)	18.4 (18.5)	595 (392)

Phosphates are basically transported by runoff and constitute a possible source of eutrophication of waters. However, phosphate fixation on clay minerals, along with its interaction with other soil components, was also estimated, although the mobility of phosphate is usually very low in relation to other mineral nutrients. The amount of phosphate adsorbed by soil depends greatly on pH, particle size distribution, and organic matter.

Nitrate is the major nitrogen-derived pollutant and, because of its high mobility, the main source of groundwater contamination. As well as land qualities associated with rainfall partitioning, this contamination risk is also predicted by cation adsorption and denitrification.

Risk of retention of the heavy metals copper, zinc and cadmium, by soils is assessed from pH, as indicative of soil carbonate content, the main land characteristic controlling the different reactions. In addition, particle size distribution, CEC and organic matter content are included in the decision tree as diagnostic criteria.

In relation to pesticide both hydrophilic and hydrophobic behaviour in soil, two major processes, sorptiòn and degradation, are considered. Organic matter content strongly affects adsorption-desorption and biodegradation of many pesticides, although other soil properties such as particle size distribution and CEC are also considered to be decision factors.

User interface

Following the general scheme of MicroLEIS^{TM} [12,14], one of the most important parts of this approach is a user-friendly front-end, which allows the model to be easily applied. The core of the evaluation models (decision trees) were initially developed within the ALES framework [30], and then translated into Microsoft C^{TM}. However, an important part of the evaluation approach is a Nantucket CLIPPER^{TM} (Version 5.1) program to automate this application, with the following major characteristics: i) interface with basic spatial databases, ii) 'pop up' screens showing codes, types or classes of land characteristics, iii) individual and batch processing modes, iv) hypothetical scenario evaluations, v) link with a GIS.

This menu-driven operating mode uses menus to present the alternatives, and to prompt the user to respond. From each menu, the 'Explanation' option provides detailed information on the corresponding step. Many input-screen fields use codes, which are included with the software in the form of indices, themselves viewed by use of the <F1> key while entering/editing data. These programmes are largely self explanatory.

Another interesting facility of the model front-end is the option to formulate hypothetical climate change scenarios, which can be useful as tools to design adaptation strategies to climate changes. These 'what-if' scenario studies are critical pieces of the puzzle in the understanding of global change. The user has the option to generate hypothetical predictions by changing the base climate related variables. So, it is possible to predict the impact of climate changes on field vulnerability to soil erosion or contamination. Within the models it is possible to define any arbitrary set of climate perturbation(s) as the hypothetical climate change. For example, maximum and mean precipitation (%), and mean temperature (°C) are climate related factors which could be applied as climate change by increment (+ or -). Output results for an evaluation scenario in i) tabular, ii) graphical, or iii) CSV format presentation, can be displayed or deleted by selecting the corresponding file. This prediction approach runs on an IBM compatible PC.

EXAMPLE OF AN APPLICATION: ANDALUCIAN SCENARIOS

A point-to-point application of the evaluation modelling approach was carried out, for the current bio-physical situation of Andalucia Region, and for two climate change scenarios. Andalucia covers 87.599 km^2, and is located in the southern part of Spain: N36° 00' to N38° 44', and W01° 37' to W07° 31'. The observation points are representatives of the 62 Andalucian natural regions: 8, 6, 7, 11, 7, 9, 5 and 9 from Almeria, Cadiz, Cordoba, Granada, Huelva, Jaen, Malaga and Sevilla Provinces, respectively [2]. The corresponding extensions of these natural regions are used to make an approximated spatial extrapolation so as to cover the whole Andalucia Region.

Current situation

Mediterranean climates and ecosystems have a very restricted distribution, probably more restricted than any other climatic zone or major ecosystem type of the world. The lands are open transitional zones between moist and arid biomes. They have been subjected to several palaeoclimatic changes. Normally, they show a rough topography and a diverse relief, so that they are very fragmented. Andalucia is a typical region of the Mediterranean area.

For each one of the 62 natural regions a representative meteorological station was selected. As an example of these datasets, the climatic data of Sevilla province are summarised in Table 4. Sevilla has warm and very dry summers and cold and wet winters, during which most of the precipitation occurs (about 600 mm per year). As in any Mediterranean area, the seasonal distribution of precipitation, with summers extremely dry, is not appropriate for crop growth. Therefore, the agricultural production systems depend basically on available water resources (irrigation water). Also, the strong inter-annual variability of precipitation, with often long drought periods (e.g., 1990-present; Table 4), is other typical limitation of Mediterranean agriculture.

The distribution of benchmark soils in Andalucia Region is shown in Table 5 according to Soil Taxonomy [33]. The morphological and analytical properties of these 62 soils are very different, along with their agricultural suitability and environmental vulnerability [2]. However, from an agricultural point of view three Orders: Alfisols, Entisols and Vertisols, can be selected as the most important.

The typical Alfisol profile (Typic Rhodoxeralf) consists of:

i) a ploughed topsoil of reddish yellow sandy clay loam;
ii) an upper subsoil of red sandy clay; and
iii)a lower subsoil of reddish yellow sandy loam, extremely calcareous.

Table 5. Distribution of the 62 selected benchmark soils in Andalucia, according to the USA Soil Taxonomy Classification: Great Group category

Great group soil type	Number of benchmark soils	Representative area, km^2
Haploxeralfs	5	7702
Palexeralfs	3	4130
Rhodoxeralfs	7	7071
Haplargids	1	1248
Camborthids	1	1201
Fluvaquents	3	2229
Arents	1	624
Xerofluvents	4	5014
Xerorthents	8	10316
Eutrochrepts	1	2989
Xerochrepts	11	16964
Cryumbrepts	1	1136
Xerumbrepts	1	1507
Rendolls	2	2602
Haplustolls	1	1369
Haploxerolls	2	2328
Palexerults	1	3747
Chromoxererts	7	11960
Pelloxererts	2	3137
Total	62	87274

The typical Entisol profile (Typic Xerofluvent) consists of:

i) a ploughed topsoil of grey clay loam, with many calcareous nodules; and
ii) a subsoil of greyish brown clay loam, strongly calcareous.

The typical Vertisol profile (Typic Chromoxerert) consists of:

i) a ploughed topsoil of dark greyish brown clay;
ii) an upper subsoil with many calcareous nodules; and
iii) a lower subsoil of light yellowish brown clay, strongly calcareous.

The site and soil-related land characteristics of the 62 benchmark soils which are input parameters of the evaluation models are presented in Table 6. The traditional crops in Andalucia can be divided into two main categories: rainfed crops (wheat, barley, sunflower, and sugar beet) and irrigated crops (potatoes, corn (maize), cotton, and rice). The rainfed crops are autumn sown, except sunflower, and the irrigated crops are spring sown. Although irrigation is not needed for rainfed crops, their production increases considerably with the water supply. It is interesting to point out the big difference in rainfed crops production between the different soil types. The soil water holding capacity appears to be the major reason for this behaviour. In this sense, Vertisol soils have a clear dry-farming vocation because of their high water holding capacity.

Climate change scenarios

The Mediterranean climate is characterised by spatially highly variable rainfall with a strong winter maximum, large inter-annual variability and frequent extreme events such as droughts, all of which combine to generate sensitivity to physical land degradation and vegetation cover. Climate, therefore constitutes the boundary condition for land degradation in the Mediterranean [3]. In order to apply the land evaluation approach, two climate change scenarios were constructed (Table 7). The first was defined by considering the prolonged drought of the last 5 years. This climate perturbation was calculated with reference to the meteorological records from Sevilla station, in order to establish the appropriate increments of temperature and precipitation. This climate perturbation was then applied to the 62 representative stations. The second scenario is based on a GCM-predicted climate change in the southern Mediterranean region for the year 2050 (after Kenny *et al.*, [23], Table 7). This large geographical area prediction referred to the winter and summer periods of the year. Changes for the missing spring and autumn periods were derived by linear interpolation.

Table 6. Summary of input land characteristics of the 62 Andalucian benchmark soils

Land characteristic	(Range) Dominant
Site - related characteristics	
Landform	(plan - mountain) hill
Slope gradient %	(0.7 - > 30) 2
Groundwater table depth m	(1 - > 10) > 10
Soil - related characteristics	
Drainage	(poor - excessive) well
Particle size distribution*	(sand - clay) clay
Superficial stoniness	(nil - abundant) nil
Organic matter* %	(0.14 - 4.32) 1.59
pH*	(5.1 - 8.7) 7.4
Cation exchange capacity* meq/100 q	(2.50 - 50.40) 17.46
Sodium saturation* %	(0.2 - 11.90) 2.70

* Soil parameters measured within the soil section 0 to 50 cm.

Table 7. Climate change perturbations generated by the present drought in Sevilla, and by prediction in the southern Mediterranean region (after Kenny *et al.* [23])

Scenario (years)	AT, °C				AP, %			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
First scenario (1990-94)	+0.00	+0.80	+0.73	-0.66	-54.0	-12.2	-61.0	-17.3
Second scenario (2050)	+1.50		+2.00		-3.0		-12.0	

Note: Period of the year: Winter (Dec-Feb), Spring (Mar-May), Summer (Jun-Aug) and Autumn (Sep-Nov). Changes for missing periods were achieved by linear interpolation.

Land evaluation results

The water erosion vulnerability classes for the actual situation are summarised in Table 8. Overall, for rainfall erosion, 16 % of Andalucian lands are at a high level of risk (Classes V8 to V10), and a further 58 % at a medium level (Classes V4 to V7). The highest risk areas are located in Almeria, south-west Cordoba, south Granada and north-east Jaen. These areas are characterised by a very broken relief, high intensity of the rainfall and medium soil texture. The medium risk areas are more scattered, Sevilla Province having most land in this vulnerability range. Rainfall intensity is the main limiting factor of this risk area. The lowest vulnerability lands are located in north-west Cadiz, Granada and south Huelva, including many soils with the highest agricultural suitability.

In the first simulated scenario, as a consequence of the current drought, in 59 % of Andalucian land the erosion risks decrease compared to the current situation; while in 24% of the land the risks increase (Table 8). The first area is located in the uplands of Cordoba, and on the very calcareous soils of Granada and Jaen. The second area corresponds basically to the central part of Almeria, with soils on steep slopes.

The second scenario, corresponding to the predicted climate perturbation by the year 2050, results in a different distribution of land vulnerability classes (Table 8), compared to the current situation and the first scenario. In contrast with the latter, erosion risk decreases in 18 % of

Table 8. Summary of evaluation results of soil erosion risk assessment in Andalucia, for the current situation and for simulated climate change scenarios

Land and vulnerability class	Current situation		First scenario		Second scenario	
	km^2	%	km^2	%	km^2	%
			Water erosion			
V1. None	4253	5	4253	5	4253	5
V2. Very Low	3906	4	6376	7	6219	7
V3. Low	14643	17	15752	18	13285	15
V4. Moderately Low	13918	16	10339	12	12963	15
V5. Slightly Low	5177	6	8300	10	5247	6
V6. Slightly High	21219	24	18998	22	20952	24
V7. Moderately High	10573	12	10205	12	5826	7
V8. High	1887	9	8847	10	12569	14
V9. Very High	4925	6	1804	2	3560	4
V10. Extreme	773	1	2400	3	2400	3

Andalucian lands, but increases in 47 % of the land. The first area is located in southern uplands of Cordoba, central Granada, northern Jaen and in the best agricultural lands of the central part of Sevilla Province. The second area corresponds to north-west Almeria, the northern uplands of Cordoba, north-west Granada and southern Jaen.

The agricultural contamination vulnerability classes for the current situation are summarised in Table 9. Overall, for the four contaminant types: phosphorus, nitrogen, heavy metals and pesticides, 27 % of Andalucian land is at a high level of risk (Class V4), and a further 33 % at a medium level (Class V3), with pesticides the highest risk. On the contrary, 40 % of the land presents no or low risk (Classes V1 and V2) of contamination. The high risk areas are scattered, the littoral agricultural lands presenting the highest values. These areas are characterised by sandy textured soils, and are frequently dedicated to irrigated crops. The highest frequency (51 %) of the highest vulnerability class is for pesticide contamination; and heavy metals are the highest frequency (23 %) of lowest vulnerability class.

For the first simulated scenario, the modelling approach predicts that in 40 % of Andalucian land contamination risks decrease compared to the current situation; while in 60 % of land the risks increase (Table 9). The first area is mainly located in lowland Cordoba, littoral Huelva, Malaga and the best agricultural land of Sevilla Province. The second area is located in littoral Cadiz and upland Jaen. Considering each type of contaminant separately,

Table 9. Summary of valuation results of soil contamination risk assessment in Andalucia, for the current situation and for simulated climate change scenarios

Land vulnerability class	Current situation		First scenario		Second scenario	
	km^2	%	km^2	%	km^2	%
			Phosphorus Contamination			
V1. None	13352	15	14332	16	14332	16
V2. Low	13786	16	11913	14	11913	14
V3. Moderately	23653	27	25769	30	25769	30
V4. High	36483	42	35260	40	35260	40
			Nitrogen Contamination			
V1. None	12657	15	21454	25	21454	25
V2. Low	45772	52	41057	47	42394	49
V3. Moderately	25140	29	24763	28	23426	27
V4. High	3705	4	0	0	0	0
			Heavy Metals Contamination			
V1. None	19672	23	24180	28	24180	28
V2. Low	11546	13	5486	6	5486	6
V3. Moderately	45053	52	52543	60	52543	60
V4. High	11003	13	5065	6	5065	6
			Pesticides Contamination			
V1. None	8936	10	6735	8	6735	8
V2. Low	11410	13	10085	12	10085	12
V3. Moderately	21989	25	15178	17	15178	17
V4. High	44939	51	55276	63	55276	63

for heavy metals and pesticides the increasing values are higher than the decreasing ones, while for phosphorus and nitrogen they are lower. In the second scenario, the modelling approach predicts almost the same results as in the first scenario (Table 9). Only a little difference is shown for nitrogen contamination vulnerability.

The major bio-physical attributes influencing soil erosion and contamination risks have been considered in the evaluation approach. However, other important attributes referred to land use and management have not been taken into account, such as land use type, crop rotation and the use of animal manures.

Reaction from local staff to the quality of the evaluation results for the current situation in Andalucia was positive, although additional work on sensitivity and validation testing are needed in order to improve the prediction capacity of the risk evaluation approach. It must not be forgotten that each observation point does not necessarily reflect the land properties of the whole natural region. Soils and climates vary widely at all scales both within and between individual landscapes. However, this land vulnerability evaluation approach was developed to be a large scale risk assessment at the country level. Therefore, policy-makers and farmers in higher risk areas should be aware of likely soil degradation processes, and look for additional confirmatory information.

CONCLUSIONS

Land evaluation appears to be a useful way to develop the capability to predict land degradation risks, or vulnerability, caused by interactive changes in land use and climate. Following a standard scheme of land evaluation, an expert modelling approach was developed for qualitative assessment of soil erosion and contamination risks at the regional scale. The evaluation approach predicts that currently 16 % and 27 % of the Andalucian land area is at increased risks of soil rainfall erosion and contamination, respectively. For the simulated current drought scenario, and if the predicted Mediterranean climate change by the year 2050 is met, changes in rainfall amount affected erosion risks strongly, but these changes proved to have little direct influence on contamination vulnerability.

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