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Present and future of desertification in Spain: Implementation of a surveillance system to prevent land degradation

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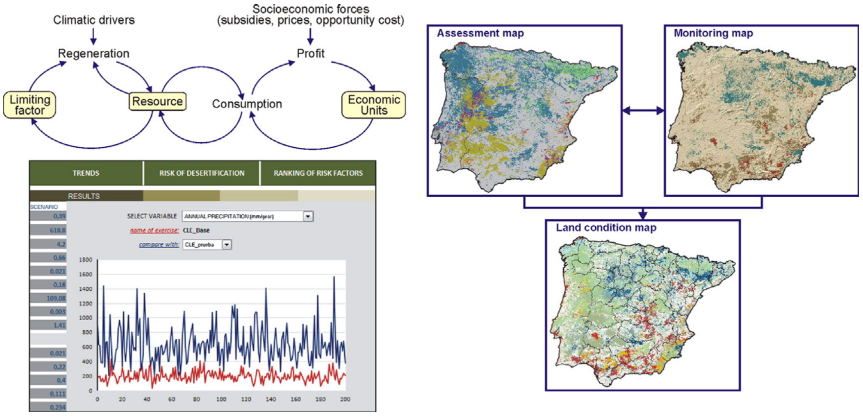
HIGHLIGHTS

- Early warning systems based on simulation models allow to anticipate desertification.
- Land degradation maps help identifying prior areas to implement solutions.
- In Spain 20% of the territory is degraded; an additional 1% is actively degrading.
- The risk of desertification is high in crop systems and low in rangelands.
- Main driving forces in land-uses under study is precipitation.

GRAPHICAL ABSTRACT



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ABSTRACT

Mitigation strategies are crucial for desertification given that once degradation starts, other solutions are extremely expensive or unworkable. Prevention is key to handle this problem and solutions should be based on spotting and deactivating the stressors of the system. Following this topic, the Spanish Plan of Action to Combat Desertification (SPACD) created the basis for implementing two innovative approaches to evaluate the threat of land degradation in the country.

This paper presents tools for preventing desertification in the form of a geomatic approach to enable the periodic assessments of the status and trends of land condition. Also System Dynamics modelling has been used to integrate bio-physical and socio-economic aspects of desertification to explain and analyse degradation in the main hot spots detected in Spain.

The 2dRUE procedure was implemented to map the land-condition status by comparing potential land productivity according to water availability, the limiting factor in arid lands, with plant-biomass data. This assessment showed that 20% of the territory is degraded and an additional 1% is actively degrading. System Dynamics

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2dRUE procedure
System Dynamics modelling

modelling was applied to study the five desertification landscapes identified by the SPACD. The risk analysis, implemented on these models, concluded that 'Herbaceous crops affected by soil erosion' is the landscape most at risk, while the Plackett-Burman sensitivity analysis used to rank the factors highlighted the supremacy of climatic factors above socioeconomic drivers.

1. Introduction

The development of methodologies and tools for monitoring and assessing desertification is encouraged by the United Nations Convention to Combat Desertification (UNCCD) through National Plans of Action (UN, 1994). This is a response to the major threat to drylands with direct impact on human well-being and social welfare, as Millennium Ecosystem Assessment warns (MA, 2005; Vogt et al., 2011).

Following this topic, the Spanish Ministry of Agriculture, Food, and Environment reaffirmed its commitment by preparing its Plan (MAGRAMA, 2008). First, the Spanish Plan of Action to Combat Desertification (SPACD) established desertification landscapes on considering criteria that take into account the definition of desertification given by UNCCD, where land degradation results 'from various factors including climatic variations and human activities'.

Most desertification landscapes have been identified in arid lands according to specific land uses and the natural resource affected by it: (1) irrigated crops that trigger desertification processes linked to groundwater exploitation in inland and coastal areas; (2) agro-silvo-pastoral systems and overgrazing, specifically Dehesa rangelands in western continental areas; (3) degraded shrublands and wastelands distributed throughout the drylands; (4) woody crops affected by soil erosion, such as olive orchards and vineyards in southern continental areas; and (5) extensive rainfed herbaceous crops affected by soil erosion in the Ebro and Guadalquivir river valleys.

In all of these cases, a common pattern can be drawn: sudden land-use changes driven by abrupt transformations of socioeconomic conditions that trigger physical degradation processes, as reported in a large number of studies (see for example Foley et al., 2005 and Upadhyay et al., 2006). These state that land-use changes leading to environmental degradation usually occur where the new use does not match the soil's natural capability, and these changes are referred to as land-use conflicts (Pacheco et al., 2014; Valle Junior et al., 2014).

Secondarily, the risk of desertification was calculated. The methodological approach was based strictly on the principles of the UNCCD. The SPACD considered four indices at the sub-basin level that work additively: aridity, soil erosion, cumulative percentage of surface area burnt by wildfires in the period 1996/2005, and aquifer overexploitation according to the net groundwater balance. Each of these indices was transformed into qualitative classes. The final aggregation yielded the main areas prone to desertification.

The SPACD was the first full assessment of desertification in Spain. However, it has to be considered as a starting point that can be improved. The aim of this paper is to present the most recent developments that followed the SAPCD (Sanjuán et al., 2014; Rojo et al., 2015). They are supported by two methodological approaches that respond to the major concerns of the scientific community: "the lack of sufficient and integrated monitoring and assessment" (Vogt et al., 2011).

On one hand, the 2dRUE tool, as originally was published (del Barrio et al., 2010), is a low-cost methodology that (1) uses open-access data and (2) offers verifiable and easily understood maps of land condition after a complex computational calculation routine. The Integrated Evaluation System and Monitoring of Desertification, an explicit goal of the SAPCD, has updated a methodology based on the Rain-Use Efficiency (RUE) concept to assess land condition for the period 2000–2010 (Sanjuán et al., 2014).

The 2dRUE methodology has been officially adopted by Spain (Sanjuán et al., 2013) and Portugal (Rosario et al., 2015) to report regularly to the UNCCD. It has also been implemented in different regions around the world like the Maghreb, Sahel, north-eastern Brazil, and Mozambique; it is currently being applied to study land degradation in China (Gao et al., 2014).

On the other hand, a collection of multidisciplinary simulation models has been developed to evaluate the risk of desertification with an alternative approach, in the aforementioned landscapes. These integrated assessment models are adaptations of a Generic Desertification Model (GDM; Ibáñez et al., 2008).

These System Dynamics (SD) models are meant to aid in the understanding of desertification landscapes. They highlight the interaction between environmental and socioeconomic variables, clarifying the processes and drivers behind land use and desertification. Each model is intended to be a 'means of exploration' (Oxley et al., 2004) for a better understanding of how systems may behave.

Given the exploratory nature of these models, they are not meant for prediction or forecasting, even though they provide outputs over time periods (Perry and Millington, 2008). Therefore, application in sparse-data areas is even possible in order to reinforce a conceptual model (Alcalá et al., 2015). Thus, the aim is to get qualitative rather than quantitative outputs to answer basic questions such as: is the degradation risk high or low? Do human activities exert a strong influence on degradation?

Specifically, the purposes of this family of models were to assess (1) the risk of degradation that a land-use system is running, giving shape to an early-warning system that can help to prevent desertification; and (2) the degree to which different factors would hasten degradation if they changed from the typical values they show at present.

In our opinion, anticipation should be the main strategy to combat land degradation in drylands. This paper presents tools for preventing desertification in the form of a geomatic approach to enable the periodic assessments of the status and trends of land condition. Also SD models fill knowledge gaps in complex ecological-economic systems (Costanza et al., 1993) and 'integrate bio-physical and socio-economic aspects of desertification through a robust framework that links the drivers, process, and symptoms of desertification' (Vogt et al., 2011).

2. Methods

The technical tools applied here to study and help prevent desertification are Geomatics and SD models, submitted to different analyses. A technical appendix is provided to describe the collection of methods used in this work, while brief description is provided below.

2.1. The 2dRUE procedure

The empirical method 2dRUE was used to assess land condition in Spain. Its rationale, assumptions, and algorithms are fully described in del Barrio et al. (2010). The method has been coded as a free open-source library of functions in R (The program is called r2dRue; Ruiz et al., 2011a), a language for statistical computing and graphics.

The use of RUE for assessing and monitoring land degradation by geomatic methods has become an established approach since Prince et al. (1998) applied it for the first time in the Sahel. RUE is currently the most widely accepted approach to estimate ecosystem conditions in drylands (Veron et al., 2006). It is an appointed metric for the UNCCD mandatory impact indicator on land-cover status (Orr, 2011).

2dRUE is based on the Rain-Use Efficiency (RUE) concept, which was originally defined as the ratio Net Primary Production to precipitation over a given time period (Le Houerou, 1984). This ratio is a suitable descriptor of ecosystem condition because it can be higher only if the soil remains fully functional. However, the straight application of RUE poses some limitations that are overcome with 2dRUE.

2dRUE was implemented in accordance with the UNCCD Strategic Objective 2 (To improve ecosystem condition) which includes mandatory progress indicators (Trends in the Land Cover and Trends of Land Productivity or Functioning of the Land).

2.2. System Dynamics modelling and coupled analyses

A SD model consists of a system of ordinary differential equations that makes a stock-and-flow representation of the system under study. The model's structure as a whole, which is made up of causal feedback loops including non-linear relationships and delays, constitutes a holistic and easily overlooked cause of its behaviour (Forrester, 1961; Sterman, 2000).

Models included in the Integrated Evaluation System and Monitoring of Desertification promoted by the SPACD stem from a GDM that embodies the interaction between economics and ecology the link of which is the natural resource under exploitation (Fig. 1).

GDM models are a cocktail of endogenous variables, i.e. explained by others, and exogenous variables, i.e. parameters or factors affecting the system but not affected by it. The former category contains variables such as soil thickness, infiltration, shrub biomass, primary production, groundwater reserves, pumping, etc. Factors are divided into environmental drivers (precipitation, temperature, soil porosity, bedrock-weathering rate, etc.) and socioeconomic drivers (input/output prices, labour cost, subsidies, etc.).

These models are lumped spatially, since their outputs refer to the entire area modelled, which is an ideal, representative piece of the modelled land use (average-sized farm) with homogeneous topographical, biophysical, and managerial characteristics. Time is treated in a quasi-continuous way, i.e. outputs are provided for each time step (Kelly et al., 2013), and the system is described at an annual time scale.

The default use of any SD model is simulation: it is fed with a scenario given by numerical values of exogenous variables and then produces temporal trends for all the endogenous variables. On the basis of repeated simulations, we have implemented a methodology to assess the risk of desertification.

This analysis looks for the final stock of key variables over the long term given current conditions. In this way it tries to foresee the effects of today's land-use policies, serving as an early-warning system. There are two categories of temporal trends yielded by GDM models (Fig. 2). Those corresponding to stable outputs are tagged as sustainable and those showing the extinction of the resource or some other socioeconomic magnitude are considered to be desertification.

The casuistic of possibilities within this range is the objective of the risk analysis. Particularly, the risk of desertification is associated with the probability of losing a certain amount of a key resource during a given number of years, as estimated over a great number of stochastic simulations. More specifically, a thousand model simulations are run under randomly generated scenarios of some parameters, for instance annual precipitation, prices of inputs, and subsidies. The resulting 1000-time trajectories of the key resource variables are recorded together with the number of years required to lose a critical amount of resource.

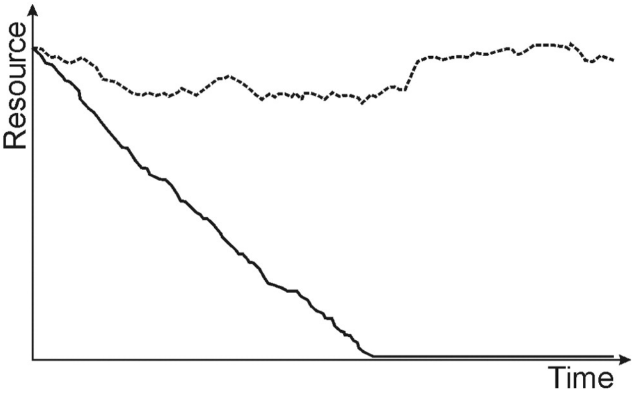


Fig. 2. Archetypes of temporal trends for sustainable scenarios (dotted line) and those in which desertification occurs (solid line).

To assess the degree to which different factors would hasten degradation if they changed from their current typical values, we conducted a sensitivity analysis. The ranking of factors relies as well on SD models. To find the most likely parameters or factors that would hasten degradation, we performed a Plackett-Burman sensitivity analysis (PBSA, Plackett and Burman, 1946). This is a statistically sound method that measures the effects of each parameter on target output variables in an efficient way in terms of the number of scenarios needed.

2.3. Study area

The purpose of SAPCD is to study desertification in Spain. In this way the scope of 2dRUE was the entire country (505,492 km^2). The reporting period was 2000–2010. The spatial resolution was 1 km and the time resolution was 1 month. The input data were: (1) Spot Vegetation NDVI S10 (VITO, 1998); (2) Climate archive 1970–2010 (Ruiz et al., 2011b); and (3) CORINE LC 2006 (EEA, 2007).

For SD models the strategy was to implement one model per desertification landscape. GDM set of equations was adapted to three versions that allow all of them to be included: (1) hydrological models linked to irrigation agriculture (HIA; Martínez–Valderrama et al., 2011) for landscape 1; (2) water erosion in rangelands and shrublands (ERS; Ibañez et al., 2014a) for landscapes 2 and 3; and (3) water erosion in extensive croplands (EEC; Ibañez et al., 2014b) for landscapes 4 and 5.

The selected case studies are located in the aridity map of Spain (Fig 3.). Models have been parameterized for eastern La-Mancha aquifer (landscape 1), Dehesas rangelands in Extremadura (landscape 2), Sierra de Los Filabres rangelands in Almeria province (landscape 3), olive

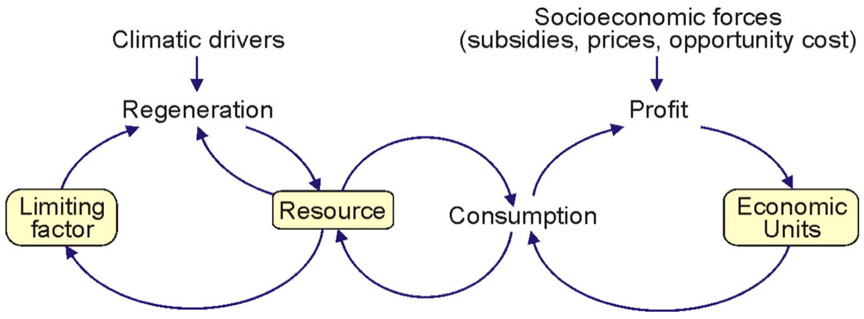


Fig. 1. General overview of GDM. Economic and ecological subsystems are coupled, giving rise to interactions that are at the core of sustainability and land degradation.

orchards in Córdoba (landscape 4), and wheat/sunflower crop rotation in Córdoba (landscape 5).

3. Results

3.1. Land condition: assessment and monitoring

The main results from the 2dRUE analysis for Spain during the period 2000–2010 are summarized in Table 1 and Fig. 4.

Regarding assessment, the 20% of the Spanish territory is categorized as being under a Degraded state, with relatively low values of biomass and productivity. An additional 30% is Productive with low-biomass land. At the other end, the states of greater ecological maturity, i.e. Productive high biomass, Mature, and Reference performance, added together reached only 30%. Therefore it can be concluded that the simplified or simply degraded states are clearly dominant.

The most important finding from the analysis of the ecology tendencies is the low proportion of land in the class Degrading (1%). This figure is consistent with results from applying the same method in other areas. For instance, the proportion of degraded land found in this study for the Maghreb (0.7%) can be more consistently included within other applications of 2dRUE such as the Iberian Peninsula (two periods) or north-eastern Brazil, all of which were below 2%. More extreme cases were 16% in Palestine and 19% in Mozambique (Alkhouri, 2012; Zucca et al., 2012; Sanjuán et al., 2014; Rosario et al., 2015). One immediate implication of this result is the scarce coverage of land with this tendency, which could be addressed by conservation policies; for this purpose 2dRUE can be a valuable tool.

Detailed Assessment and Monitoring maps are attached in Appendices B and C.

3.2. Desertification risk

Risk is estimated according to the percentage of simulations in which key resources are exhausted. Specifically, the case studies reflected in the SPACD focus on losing groundwater reserve, irrigation surface area, soil thickness, pasture, and shrub biomass (Table 2).

The results are interpreted as follows. For instance, for landscape 3 the risk of losing the current stock of shrub biomass is estimated 4.7% within 93 years. For the broadest time horizon (2000 years) all the shrubs disappear (the risk goes up to 100%) within 192 years.

The critical case, in light of this analysis, involves the extensive croplands in Córdoba province. This system has shown a collapse in 100% of 1000 simulations with period times of 100 years (collapse takes only 61 years). Irrigated crops in eastern La Mancha aquifer are also prone to degradation, but in this case unsustainability affects the economic side of the system. Indeed, the irrigation surface area plummets in 47 years in 88.2% of simulations.

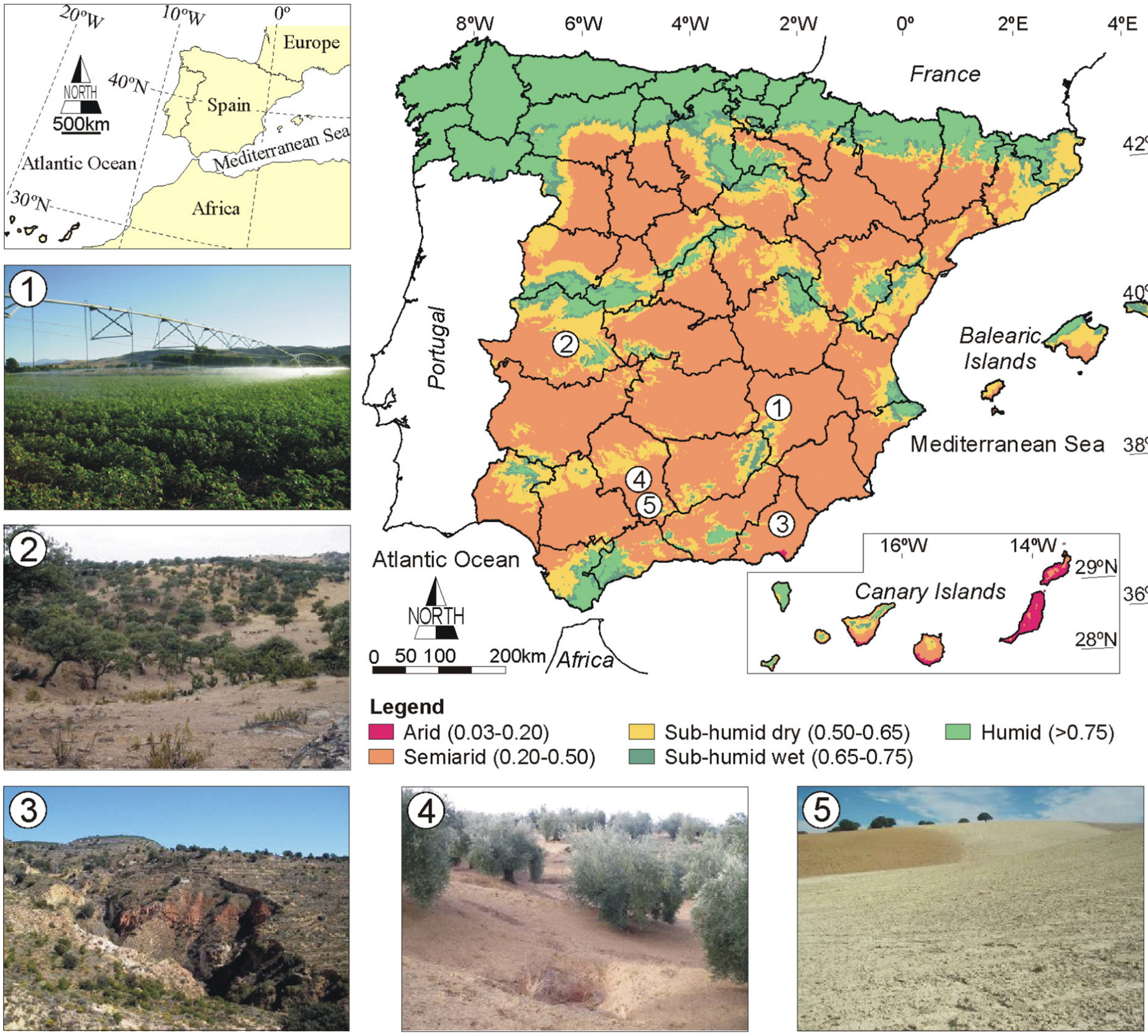


Fig. 3. Drylands in Spain and location of the five case-studies, one per landscape of desertification.

Table 1
Summary of 2dRUE results according to assessment and monitoring classes for land conditions in Spain, period 2000–2010.

Assessment	Monitoring				Total, km^2	Total, %
	Degrading	Fluctuating	Increasing	Static		
Underperforming anomaly	1841	30,487	11,427	28,021	71,776	14
Baseline performance	447	8128	4932	9124	22,631	4
Degraded	1065	19,679	45,601	32,875	99,220	20
Productive low biomass	1241	54,638	28,114	70,025	154,018	30
Productive high biomass	661	19,697	30,442	23,050	73,850	15
Mature	320	5659	34,443	19,083	59,505	12
Reference performance	191	1526	7781	6157	15,655	3
Overperforming anomaly	165	1607	3680	4025	9477	2
Total, km^2	5931	141,421	166,420	192,360	506,132	100
Total, %	1	28	33	38	100	

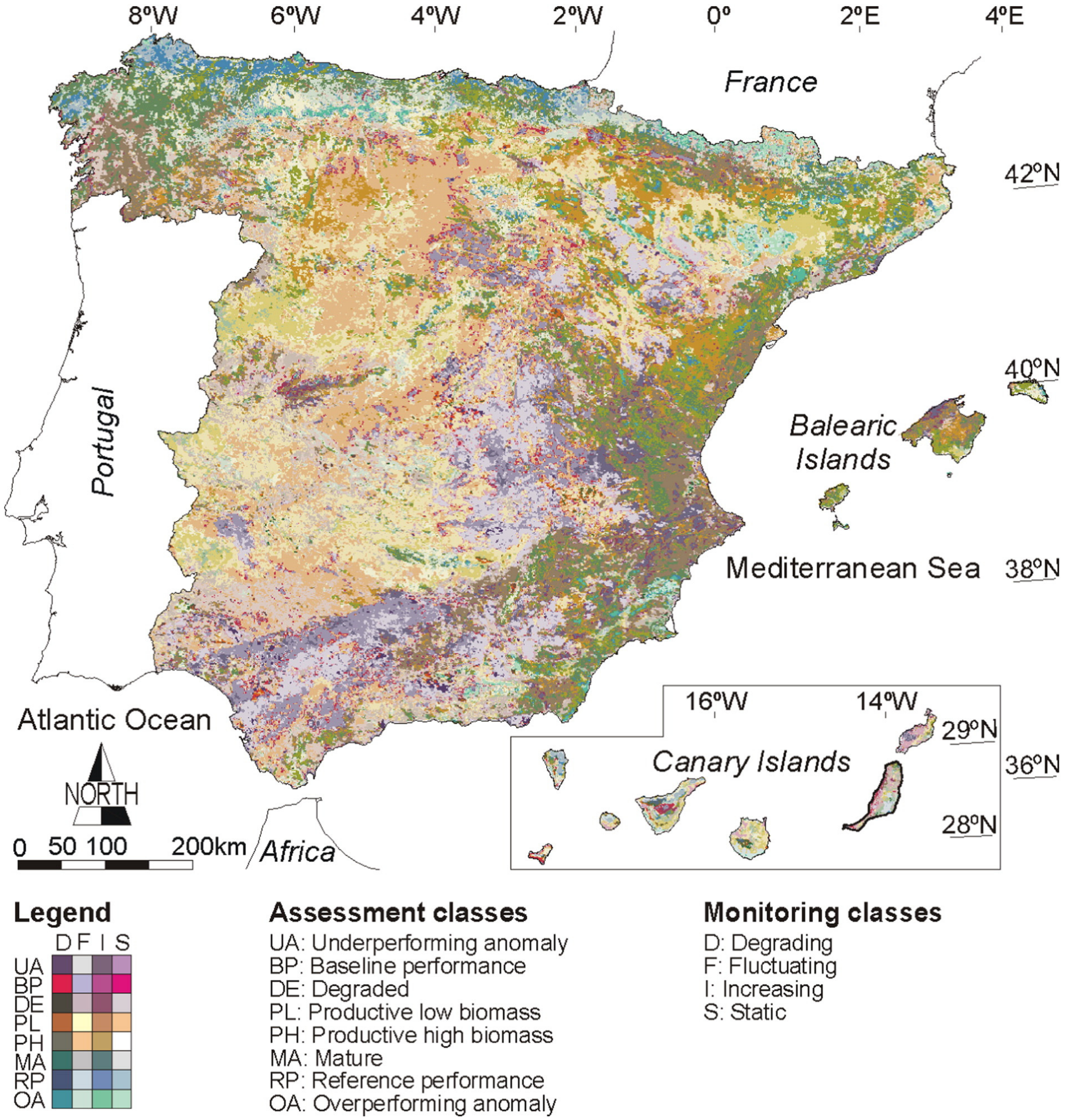


Fig. 4. Land condition map for Spain, period 2000–2010.

Table 2
Risk of desertification for the five case studies of the SPACD.

Case studies[a]	Desertification landscape	Model[b]	Key resource	Period time: 100 years		Period time: 2000 years	
				% Risk	Time elapsed	% Risk	Time elapsed
Eastern La Mancha aquifer	1	HIA	Groundwater reserve	0	–	0	–
			Irrigation surface	88.2	47	100	58
Dehesas in Extremadura	2	ERS	Soil thickness	0	–	100	352
			Pasture biomass	0	–	0	–
Sierra de Los Filabres rangelands in Almería province	3	ERS	Soil thickness	7.7	92	100	186
			Shrubs biomass	4.7	93	100	192
Olive orchards in Córdoba	4	EEC	Soil thickness	0	–	100	169
Wheat/sunflower crops rotation in Córdoba	5	EEC	Soil thickness	100	61	100	61

[a] Location in Fig. 3.
[b] HIA Hydrological models linked with irrigation agriculture; ERS Water erosion in rangelands and shrublands; EEC Water erosion in extensive croplands.

In the case studies of olive orchards in Córdoba province and in Sierra de Los Filabres rangelands show mild warning levels, with the average term for soil loss being between 169 and 186 years, respectively. Dehesa rangeland is the case with the lowest risk of desertification, the average time for soil loss being 352 years.

3.3. Ranking of factors

The results for the five case studies are presented in Table 3. Only the top five factors are shown; the full results are available in Rojo et al. (2015). The PBSA results are interpreted as follows. A 10% increase in the value of parameters in the left column in Table 3 involves an increase (positive percentages) or a decrease (negative percentages) of target variables.

Table 3
Ranking of factors for the five landscapes studied, as in Fig. 1: (1) eastern La Mancha aquifer, (2) Dehesas rangelands in Extremadura, (3) Sierra de Los Filabres rangelands in Almería province, (4) olive orchards in Córdoba province, and (5) wheat/sunflower crop rotation in Córdoba province.

(1) Time for groundwater reserve loss		(1) Time for irrigation surface loss	
1. Average annual precipitation	4.9%	1. Average annual precipitation	42.8%
2. Annual EA[a] in non-irrigated surface	−4.9%	2. Irrigation system efficiency	42.6%
3. CV[b] of annual precipitation	−1.5%	3. Average price of products	34.4%
4. Average energy price	1.1%	4. Average energy price	−28.8%
5. Other costs per hectare	1.0%	5. Energy required to lift 1 m one tone	−27.9%
(2) Time for soil loss		(2) Time for pasture loss	
1. Average annual precipitation	−22.8%	1. Average annual precipitation	−22.5%
2. Initial mean SRC[c] at wilting point	−10.5%	2. Initial mean SRC at wilting point	−10.3%
3. Standard annual EA	3.2%	3. Standard annual EA	3.1%
4. Annual EA in the humid season	3.1%	4. Annual EA in the humid season	3.1%
5.Annual precipitation in the humid season	−2.8%	5. Annual precipitation in the humid season	−2.7%
(3) Time for soil loss		(3) Time for shrub loss	
1. Average annual precipitation	109.4%	1.Average annual precipitation	110.2%
2. Secondary income per breeding female	−40.1%	2. Secondary income per breeding female	−39.6%
3. Average price of products	−32.6%	3. Average price of products	−32.2%
4. CV of SRC at wilting point	18.3%	4. CV of SRC at wilting point	17.4%
5. Supplemental feed price	15.4%	5. Supplemental feed price	15.2%
(4) Time for soil loss		(5) Time for soil loss	
1. Average annual precipitation	−22.2%	1. Average annual precipitation	−19.8%
2. CV of SRC at wilting point	−6.1%	2. CV of SRC at wilting point	−6.3%
3. Months when precipitation > EP[d]	−3.5%	3. Months when precipitation > EP	−5.4%
4. Annual EC[e] under standard conditions	2.1%	4. Annual EC under standard conditions	4.5%
5. Annual EA in the humid season	1.2%	5. Annual EA in the humid season	3.5%

[a] EA, actual evapotranspiration.
[b] CV, coefficient of variation.
[c] SRC, soil-runoff coefficient.
[d] EP, potential evapotranspiration.
[e] EC, crop evapotranspiration.

For example, for landscape 1 (Table 3), a 10% increase in the average annual precipitation means that 'Time for groundwater loss' increases in 4.9%, i.e. increased degradation in precipitation delays. The ranking of the factors according to their impact on groundwater-reserve loss is not significant because it is meaningless to evaluate the impact on something that does not degrade; note that risk of desertification of this large aquifer is null due to the higher groundwater storage. This risk may increase in small aquifers during water crises associated with recurrent dry spells (Alcalá et al., 2015).

Regarding irrigation surface-area loss, it should be noted that 4 out of 5 factors are linked to the gross margin, and all of them point in a single direction. Changes in factors implying increased profits delay irrigation abandonment, i.e. time for increased irrigation surface-area loss. The importance of annual precipitation and the efficiency of the irrigation systems are remarkable. A 10% increase in these factors means delaying the loss of irrigated lands by around 42%.

In the case of the Dehesas, the main factors that could accelerate degradations are those related to precipitation and its intensity. On the contrary, socioeconomic factors do not appear to endanger these systems.

Sierra de Los Filabres rangelands are extremely sensible to changes in average annual precipitation. A 10% increase means that times for soil and shrub loss can be extended by 109.4% and 110.2%, respectively.

Factors that affect the gross margin per breeding female, and through it stocking rate, tend to occupy top-ranking positions. A 10% increase in secondary incomes shortens the 'Time for soil loss' and 'Time for shrub loss' by around 40%.

A 10% increase in annual precipitation means that 'Time for soil loss' falls by 22.2% in the case study of olive orchards and by 19.8% in herbaceous crops. When the rainfall intensity (the variable in the model is CV of soil-runoff coefficient at wilting point) increases by 10%, then 'Time for soil loss' falls 6.1% in olive orchards systems and 6.3% in wheat/sunflower crops rotation.

The variability of annual precipitation and its intensity (denoted by their coefficients of variation) shows no significant effects on soil loss in any of the case studies. Future climatic scenarios (MAGRAMA, 2014) predict a declining trend in the annual precipitation in Mediterranean areas but rainfall intensity is forecasted to increase. As the amount of precipitation has a substantially stronger impact than does intensity, the variable 'Time for soil loss' is expected to undergo some delay.

4. Discussion and conclusions

Land degradation in drylands is the environmental sequel desertification. Its main effects on soils include erosion, loss of organic matter, salinization, compaction, and sealing, degrading the services provided by ecosystems and, in turn, the functioning of coupled natural and human systems. Proper mitigation strategies should address not only such effects, but also the socioeconomic drivers causing them.

The development of an Integrated Evaluation System and Monitoring of Desertification in the SPACD includes methodologies to cope with the main challenges proposed by the UNCCD, such as early-warning systems, assessment, and monitoring procedures to produce tools that assemble the interaction between ecology of resources and socioeconomic factors.

The first methodology presented in this paper is 2dRUE. This is a cutting-edge technology, partly because (1) has evolved in a purely scientific thread, and (2) has been designed from scratch for defined stakeholders and end-users. As a result, it provides the following distinct advantages over other methods: (1) full diagnosis, separating states and trends of land degradation; (2) two-dimensional estimates of RUE at short- and long-term temporal scales, enabling better assessment of land uses; (3) incorporation of technical corrections to be applied over large territories; and (4) a legend which is intuitively understandable to lay persons while having a sound scientific basis and easy interpretation requiring only simple web-based GIS servers such as Google Earth ®.

Land-degradation map applications go beyond a coherent representation of earth ecosystems or identifying states and tendencies in ecological maturity terms. It has at least two other potential uses. One is to serve as a tool for detailed diagnosis for territorial policies; in this case those related to desertification mitigation strategies. The other is to serve as a methodological prototype for later implementations in Spain and in other countries.

As a demonstration of more elaborated products, a useful analysis results from overlapping a land-condition map with the CORINE land-use map (EEA, 2007):

1) The highest incidence of Degrading ecosystems occurs in Underperforming anomaly and Baseline performance classes (agricultural crops in both cases). To a lesser extent, this trend also takes place in Reference performance (forests) and Overperforming anomaly (agriculture vegetation) classes.
2) Often Fluctuating ecosystems are Productive low biomass (short natural vegetation or agricultural crops), Underperforming anomaly, or Baseline performance (both with agriculture vegetation). It is relatively uncommon for this trend to appear in Degraded or Mature ecosystems, in which case it would be short natural vegetation.
3) Degraded ecosystems are usually Increasing (forests), but this tendency is associated with higher levels of ecological maturity (Productive high biomass, Mature, Reference performance, and Overperforming anomaly) always in forests.
4) Conversely, the lack of a detectable trend (Static class) is more common in simplified ecosystems as Productive low biomass (short natural vegetation and agriculture vegetation), Underperforming yield, and Baseline performance (agriculture vegetation in both cases).

The second methodology presented in this paper was SD modelling, a methodology suitable to track the origin of active desertification processes. This was a critical gap announced by Diez and McIntosh (2011). It is important to remark that SPACD models sacrifice precision to generality and realism, given that their purpose is to clarify the interaction of ecology of resources and socioeconomic pressures. Their aim is to estimate the risk of desertification and establish the ranking of factors influencing the process.

A good illustration of this is given by the way in which functional forms are chosen. They are anchored to parameters that have a real counterpart. Since our concerns are focused on getting qualitative rather than quantitative outputs, theoretical functional forms were chosen on the basis of their general shape (increasing or decreasing), their economy in terms of the number of parameters required, and the plausibility of the bounds they imposed on the corresponding variables, instead of by fitting curves to data.

If forecasting is far from the goal of these models, including the estimation of the risk of desertification, it may be questioned whether all this effort is worthwhile. Or, in more specific terms, it might be asked whether qualitative output used as an early-warning system should not be achieved with much less elaborate indicators such as erosion rates for soil loss or recharge-to-discharge ratio for groundwater degradation.

One single static value of erosion rate allows a simple estimation of soil-moisture depletion by dividing it by soil thickness, and using previously bulk density to convert $\text{tn} \cdot \text{ha}^{-1}$ year^{-1} into mm year^{-1}. However, the nonlinear long-term dynamics of water erosion, typically consisting of an initial period of growth followed by a period of decline, have significant effects on soil lifespan. Current soil-erosion rates should not be naively projected onwards, especially when the fact that degradation is generally a medium- to long-term process is taken into account.

Thus, the erosion rate may vary due to changes in vegetal cover resulting from stocking-rate variations prompted by market-price alterations or by the soil-fertility loss induced by erosion. For the five case studies presented in this work, differences in 'Time for soil loss' depending on the use of single rates and SPACD models are presented in Table 4.

This divergence is largely the result of including (or ignoring) positive feedbacks that are triggered when soil disappears. Indeed, erosion exposes deeper soil layers having higher bulk density and lower porosity. The first outcome is that infiltration rates decrease and runoff increases, meaning that the erosion rate accelerates over time. The second effect, involving those cases with natural vegetation (pasture and shrublands), is that seed germination is inhibited and patches of bare soil become prominent, which in turn accelerates erosion.

In conclusion, naive projections of steady erosion rates consider a linear function for soil loss, ignoring all the feedback mechanisms underlying it. The difficulty of knowing the final balance resulting from this combination of interacting dynamic processes is evident. When dealing with ecological and socioeconomic situations, a dynamic and consistent picture would produce better estimations than would any other static procedure.

The preliminary results from desertification-risk methodology shows that soil erosion seriously threatens extensive croplands while in rangelands the problem is minor. In large inland aquifers the main problem seems to be land abandonment but not groundwater exhaustion.

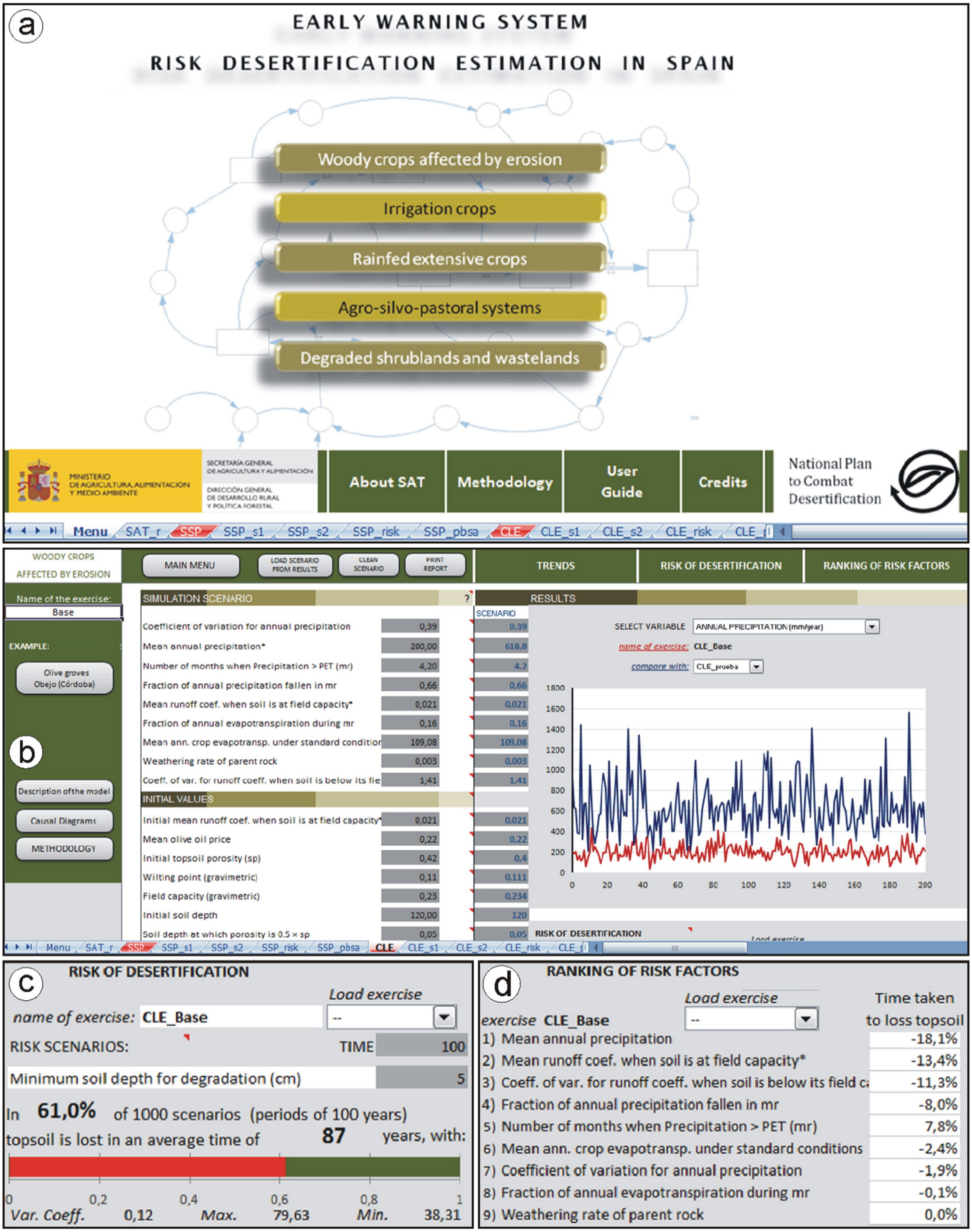
Regarding the rankings that result from the implementation of PBSA on SD models, the amount of precipitation is the main factor in the desertification process. When precipitation increases, paradoxically degradation proceeds faster in olive orchards, Dehesa rangelands, and extensive herbaceous crops, all characterized by thin soil over low-permeability bedrocks. The combined effect of high precipitation and low-permeability encourages runoff, rather than primary productivity and cover protection, leading to higher erosion rates. This matches the conclusion of Kirkby (1980), observing that Mediterranean regions fall in that fateful precipitation range, between 300 and 600 mm, of which a large part is torrential and does not allow an enduring vegetal cover, but simultaneously gives rise to the highest erosion rates and erosion risk.

Table 4
Estimation of 'Time for soil loss' (years) using two methods: (a) Static erosion rates; (b) Erosion rates from SD models.

Case study	Static erosion rates	SPACD models	% variation
Wheat/sunflower crops rotation	200	61	−70%
Olive orchards	657	169	−74%
Sierra de Los Filabres rangelands	1045	186	−82%
Dehesas in Extremadura	1739	349	−80%

The increase in precipitation nevertheless delays shrub degradation and irrigation-land abandonment. In the first case, this is because greater precipitation has an initial positive impact on the system, when vegetation development exceeds the pernicious effect of runoff. In the second case, this is because high precipitation tends to replenish the groundwater reserve.

Socioeconomic variables have proved to be important potential factors of degradation. Variations enhancing profit and therefore the size of



Name of the exercise: Base

SIMULATION SCENARIO		SCENARIO
Coefficient of variation for annual precipitation	0,39	0,39
Mean annual precipitation*	200,00	618,8
Number of months when Precipitation > PET (mr)	4,20	4,2
Fraction of annual precipitation fallen in mr	0,66	0,66
Mean runoff coef. when soil is at field capacity*	0,021	0,021
Fraction of annual evapotranspiration during mr	0,16	0,16
Mean ann. crop evapotransp. under standard condition	109,08	109,08
Weathering rate of parent rock	0,003	0,003
Coeff. of var. for runoff coeff. when soil is below its fie	1,41	1,41
INITIAL VALUES		
Initial mean runoff coef. when soil is at field capacity*	0,021	0,021
Mean olive oil price	0,22	0,22
Initial topsoil porosity (sp)	0,42	0,4
Wilting point (gravimetric)	0,11	0,111
Field capacity (gravimetric)	0,23	0,234
Initial soil depth	120,00	120
Soil depth at which porosity is 0.5 × sp	0,05	0,05

SELECT VARIABLE: ANNUAL PRECIPITATION (mm/year)

name of exercise: CLE_Base

compare with: CLE_prueba

RISK OF DESERTIFICATION

name of exercise: CLE_Base

Load exercise: --

RISK SCENARIOS: TIME 100

Minimum soil depth for degradation (cm) 5

In **61,0%** of 1000 scenarios (periods of 100 years) topsoil is lost in an average time of **87** years, with:

Var. Coeff. 0,12 Max. 79,63 Min. 38,31

RANKING OF RISK FACTORS

Load exercise: --

exercise CLE_Base	Time taken to loss topsoil
1) Mean annual precipitation	-18,1%
2) Mean runoff coef. when soil is at field capacity*	-13,4%
3) Coeff. of var. for runoff coeff. when soil is below its field c	-11,3%
4) Fraction of annual precipitation fallen in mr	-8,0%
5) Number of months when Precipitation > PET (mr)	7,8%
6) Mean ann. crop evapotransp. under standard conditions	-2,4%
7) Coefficient of variation for annual precipitation	-1,9%
8) Fraction of annual evapotranspiration during mr	-0,1%
9) Weathering rate of parent rock	0,0%

Fig. 5. (a) Main menu of the platform. (b) Screen for inputs and time trends. (c) Risk of desertification. (d) Ranking of factors.

flocks, significantly advance desertification in Sierra de Los Filabres rangelands. On the contrary, variations aimed at reducing gross margins per hectare in aquifers of eastern La Mancha anticipate the abandonment of irrigated land. A minor impact of socioeconomic drivers affects the degradation of Dehesa rangelands.

At a late stage, the use of SPACD models is intended to facilitate participatory exercises with stakeholders and end-users when special degradation risks in the corresponding land use are shown. This is a common way to convey research findings about social learning, system understanding, and experimentation to stakeholders and end-users.

Because models are fed with actual meaningful parameters, they initially reproduce the current state of the system. Participation of stakeholders and end-users can also help in improving the models as new qualitative and quantitative data are acquired.

A piece of software was programmed to optimise the analyses made (Fig. 5). The five case studies were implemented in a simulation platform programmed in Excel Visual Basic with Vensim® libraries (Ventana Systems Inc.).

Future developments include new models to cope with desertification syndromes already identified. Specifically, how salinization of coastal aquifers affects groundwater-dependent agriculture, as a continuation of the first desertification landscape, will be a forthcoming adaptation of GDM. Refining sensitivity analyses to evaluate more precisely the ranking of factors causing desertification is another goal. A variance-based sensitivity analysis has been tested for Dehesas rangelands (Ibáñez et al., 2016). The challenge is to expand this more robust methodology to all the case studies.

Another relevant methodological step would be build simulation models in order to describe how land is converted from any land use to another. Land-use interchangeability should be guided by land-condition maps as they give information on land suitability for diverse land uses. The paradigm behind this attempt is that any plan to restore soil functions and ecosystem services should have the capacity to restore the sustainability of land-use systems, i.e. preserve or bring back management options of the territory. This is a broader conception of the problem because it takes into account simultaneously all the uses in the territory instead of treating them individually in an isolated way, as the SPACD proposed.

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