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How to improve strategic decision-making in complex systems when only qualitative information is available



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ABSTRACT

This paper continues a line of research on improving strategic decisions (SD). The nature of governance issues (complex and uncertain world, lack of information, consideration of qualitative and quantitative information, participation of different actors in the decision making processes, etc.) implies that there is no unique solution or strategy in a complex system. On the contrary, there are a range of alternative strategies, which could lead to different futures (scenarios). Working with the qualitative methodology proposed allows decision makers and social actors to be more aware of the directions their decisions could lead the system; and what the key variables are for the implementation of public policies to achieve the desired (or agreed) scenario. An integrated methodology is discussed, and the process of desertification in the Canary Islands is used to illustrate it.

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1. Introduction

This article carries on the research of authors on the development of methodologies to improve Strategic Decisions (Legna Verna et al., 2005a,b; Legna Verna and González González, 2006, 2005; Legna Verna, 2010, 2007, 2000; Corral Quintana et al., 2002; Guimarães Pereira and Corral Quintana, 2002a,b). It is based on the results of a research project funded by the government of the Canary Islands to assess the process of desertification, which has been increasing over the last few decades, and to propose policies to reduce it. The research team was composed of the authors and other researchers from various departments of the University of La Laguna.

In recent years, the so called decision tools –in which decision support systems (DSS) are included– have been enhanced not only because of technology but also because of greater skills and acceptance to actually use such tools for consultation purposes. In a sense, we have been witnessing a change in the use of *decision tools* within *decision-making* processes. More accountable and inclusive governance styles have also been emerging, which highlight the fact there is not a single decision maker (there was never only one, but

now DSS developers are no longer pretending there is) but debates involving many actors that take place over policy issues. Accountability and inclusive processes have been progressively promoted in the last two decades through new legislation. Moreover, there has also been a progressive recognition that it is not at the level of *decision* that appropriate consultation, dialogue and deliberation take place among those concerned¹ with a certain *problematique*.

Environmental issues entail multiple dimensions of analysis that cannot be *amalgamated* into a single measurement scale because they belong to different aspects and actors of the processes. Actors *talk* different *languages*, express uncertainty in different ways – hence, new developments in information tools have to take into account this diversity. In the past, many *decision* systems, corresponding to institutional requests, were aimed at delivering expert knowledge to *legitimate* decisions taken. However, emerging governance styles require interfaces for the extended involvement of relevant actors (De Marchi et al., 2001). There is an opportunity here for developing these tools as platforms to involve different

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¹ These are frequently called social actors or stakeholders (North American School) and in Dutch and German literature, the *betroffenen* (those concerned). Although throughout this paper, the word actors is used, while waiting for a better term. By *actors* it is meant here, those that may affect or be affected by a “problematique”, and this includes not only those that have a stake or interest or those that play a role but also anyone who is concerned or affected by a situation.

flows of *knowledge and wisdom*. Such tools are no longer viewed as the means to legitimate decisions but rather to initiate and inform debates and decision-making processes.

As mentioned earlier, tools to inform such processes have been changing over time not only with the adoption of different technologies and design concepts, but also in the conceptual framework used. In the last few decades, DSS for environmental issues have evolved toward the integration of social research methods and institutional analysis (Guimarães Pereira, and Corral Quintana, 2002a; Paneque Salgado et al., 2009). Other authors such as Low and Astle, (2009) and Ostrom (1990, 2005) have also pointed out the importance of the social context and institutions in governance processes. In fact, several studies dealing with participation techniques and processes have been carried out with regard to natural resources management (De Marchi et al., 2000; Gamboa and Munda, 2007; Paneque Salgado et al., 2009; Khadka et al., 2013; Kangas et al., 2010).

In general, participatory methods for resource management are becoming increasingly important as a requirement for a high level of participation that has been prescribed in the environmental directives of the EU and elsewhere. Thus, several participatory approaches and methods have been proposed to facilitate an effective involvement of stakeholders in these issues. In this article, participatory modeling, and more specifically, system dynamics modeling methodology is integrated within a broader exploratory framework to facilitate the identification of the fundamental structure underlying the processing of information flows. It follows the work carried out by Videira, et al. (2003, 2009) in which, the role of collaborative environmental decision-making and the involvement of stakeholders in the development and experimentation of alternative policy scenarios is critically evaluated. Previously, d'Aquino et al. (2002) discussed the relevance of participatory modeling to deal with land-use management issues. These might be considered complex issues due to the uncertainty and the inherent variety of legitimate perspectives involved. Moreover, these approaches are particularly relevant when dealing with socio-environmental problems characterized by data scarcity, as Ritzema et al. (2010) suggested when dealing with environmental planning for the restoration of the Kolleru–Upputeru wetland ecosystem on the east coast of Andhra Pradesh in South India.

Essentially, tools to inform dialogues, debates and deliberations (TIDDD) are tools that deploy new information & communication technology (namely internet, multi-media and 3D virtual reality interfaces) in order to organize the information that feeds into a dialogue process about a governance issue. TIDDD are designed to support participatory processes. These types of tools originate from integrated assessment activities (Sors et al., 1997; De Marchi et al., 1998). TIDDD are designed for each context and audience in which they are to be used and feature *progressive disclosure of information*. They are a contribution to the implementation of the science and governance initiatives. (Corral Quintana et al., 2002; Guimarães Pereira and Corral Quintana, 2002b).

The role of information tools is not only to provide the *knowledge* to inform a debate but also to be the common ground platform through which the debate is organized, as well as to integrate other sources of knowledge that may emerge during the process. Involvement of actors is viewed as a mark of quality assurance in the decision-making processes and corresponds to the principles of extended peer review (Funtowicz and Ravetz, 1990), i.e. involving those that affect or are affected by a *problematique* to ensure higher quality of decision processes and identify different alternative courses of action (Commission-of-the-European-Communities 2001).

The first section deals with the elaboration of qualitative models; the second with the application of system dynamics based mainly on the results of the qualitative analysis; the third one the

definition of logical path of scenarios; and in the last section the authors explain how to combine these tools to select strategies.

2. The desertification process on small islands: a complex issue

Desertification is the result of the action of a set of processes that cause a decline in the biological potential of a territory and its productivity. It is basically based on the negative impact of human activities on geographical areas under arid conditions. Thus, the United Nations Convention to Combat Desertification (UNCCD) defined, in Article 1, this process as being “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities.

It is a complex phenomenon in which multiple factors of various kinds are involved. It is an environmental problem, but also a social and economic one. Desertification is not solely due to aspects such as soil erosion, loss of vegetation cover, soil salinization, loss of welfare of the population, social marginalization, etc., but also, and mainly to the interaction among all of these.

The term desertification has been incorporated into common language in recent times, although in some cases its meaning has been misinterpreted. Desertification is neither just a kind of environmental degradation nor is limited to erosion or drought processes, it is the strong existing relationship between all of them. As said before, it is not a purely environmental problem; it also has important social and economic connotations. The UNCCD in its preamble declares: “...that desertification is caused by complex interactions among physical, biological, political, social, cultural and economic”. However, it is usually not associated with the abandonment of traditional farming systems, agricultural intensification, or concentration of economic activity in coastal zones, among others.

Besides taking into account the effect of this process on human welfare in the broadest sense, it may also affect education, food and health among other societal pillars and hence the quality of life (Adeel et al., 2005).

Decision-making actions are not only complex due to these systemic interactions but also due to the involvement of different stakeholders –private and public– with specific perspectives and values and pursuing different interests. These come from fields such as environment, agriculture, hydrology, land use, education and economics, among others; and whose powers usually reside in different institutional bodies and not always even in the same administration fields. Combating desertification requires a major effort of integration, coordination and also consensus among those involved.

The Canary Islands due to its geographical location and insular character is a territory where ecosystems and agricultural systems are generally very fragile, which makes it very sensitive to these processes. In fact, there are, nowadays, areas already showing the effects of desertification, while others are clearly at high risk of suffering it.

Among the main triggers of desertification in the Canary Islands, there are both natural causes (i.e. climate, topography, soil, etc.) and those related to human activities (grazing, intensive agriculture and loss of traditional culture styles, quality and management of irrigation water, changes in the characteristics of the soil cover and its sealing, population growth,...) involved.

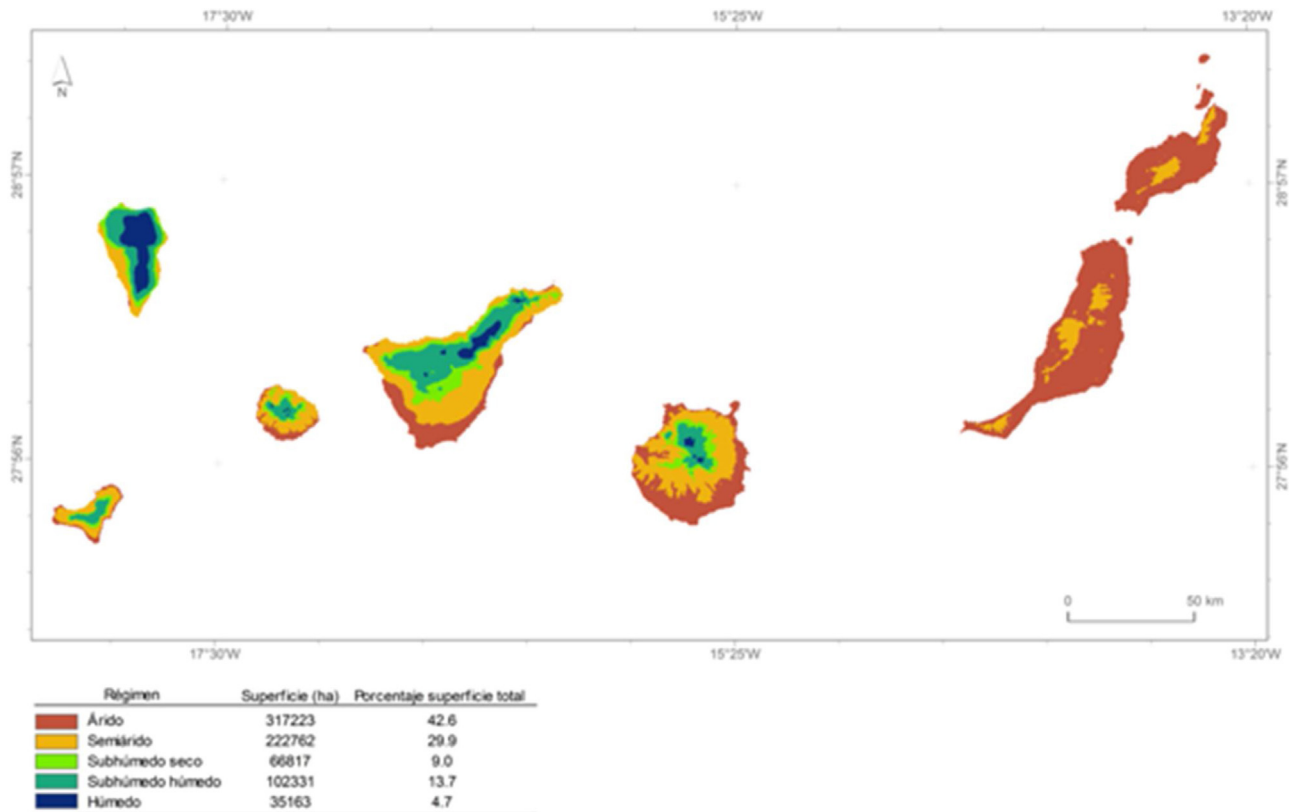
An analysis of the situation shows that about 82% of the archipelago is included within the definition of aridity and therefore at risk from desertification. The islands of Lanzarote (LZ) and Fuerteventura (FV) have 100% of their area within the arid or semi-arid regime, while on the island of La Palma (LP) only 31% of the territory might be considered as dry lands. Table 1 shows the per-

Table 1Occupied area for certain classes of aridity on each island using an aridity index (P_a/ET_0). (ET_0 based on the Thornthwaite method).⁵

Regime	LZ		FV		GC		TF		LG		LP		EH	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Arid	73352	86.8	143907	86.6	57887	37.1	32107	15.8	6220	16.9	138	0.2	3611	13.5
Semi-arid	11144	13.2	22256	13.4	66619	42.8	77976	38.3	19033	51.7	11792	16.7	13942	52.0
Sub-humid dry	–	–	–	–	15081	9.7	32919	16.2	5000	13.6	10336	14.6	3481	13.0
Sub-humid humid	–	–	–	–	14413	9.2	51944	25.5	6200	16.9	23975	33.9	5800	21.6
Humid	–	–	–	–	1825	1.2	8550	4.2	338	0.9	24450	34.6	–	–

 P_a : Annual precipitation. ET_0 : Annual potential evapotranspiration.

LZ: Lanzarote, FV: Fuerteventura, GC: Gran Canaria, TF: Tenerife, LG: La Gomera, LP: La Palma, EH: El Hierro.

**Fig. 1.** Map of the Canary Islands' aridity regime (ET_0 based on the Thornthwaite method).

centage of area and total area occupied by the different kinds of aridity on each of the islands, and the map in Fig. 1 represents the delimitation of each of these aridity classes in the archipelago.

Thus, it is clear the *problematic* involves economic, cultural and environmental variables within a social setting in which the stakeholders involved act to pursue their goals. This is the kind of reality that must be recognized when defining strategies to confront the desertification processes in the Canary Islands.

3. An integrated strategic planning methodology to tackle the case of desertification in small islands

To design strategies and policies to address complex *problematic*s such as desertification processes, methodologies allowing both an integrated view of the issue and the proposal of appropri-

ate strategies are necessary. These methodologies would “also be extended as a means to identify and design the social contexts where decisions are made or considered” (Corral and Funtowicz, 1998) In this regard a methodology that combines tools from different fields of knowledge (social, natural and exact sciences) is suggested in the present study.

The methodological integrated framework proposed in this paper to deal with the case of desertification (see Table 2) follows three phases. Firstly, a detection of the key variables that influ-

Table 2
Integrated methodology scheme.

Phase	Aim	Methodological tool
First	To determine key variables and their relationships	Qualitative model
Second	To analyze behavior and carry out simulations of the evolution of the system	System dynamics
Third	To assess action paths	Elaboration of scenarios
Fourth	To define strategies and policies to tackle desertification	

⁵ Thornthwaite (1948) developed an empirical equation for determining the monthly Evapotranspiration (ET_0) based on the average air temperature, with a correction for the astronomical length of day and number of days in the month. For a more detailed discussion of the different methods of determining the degree of aridity analysis, see Tejedor Salguero et al. (2013).

ence the problem of desertification as well as the interactions that may occur among them was performed. To do this, a qualitative model (QM) of the desertification issue was developed. The QM was based on formal and informal sources of knowledge such as an analysis of statistical data series (evolution of desertification, agricultural practices and crop yields productivity,...), interviews with experts and stakeholders, application of methods such as the Delphi method to determine the probability of certain events or the importance of the variables, among others. This first step provides an initial overview of the different variables that influence desertification, facilitating the understanding of how the variables interact with each other.

In the second phase, the qualitative knowledge attained was implemented as crucial input in the design of a dynamic model, using system dynamics methodologies. This facilitated the exploration of the structure of the system under assessment –and its social, environmental and economic dimensions– and how the most relevant variables behave over time and what effects might arise from the desertification dynamic behavior.

Finally, the results of both the qualitative model and the system dynamics modeling were used to construct different scenarios integrating the temporal evolution of the most relevant variables. This enabled us to identify existing systemic nodes that should be taken care of and to analyze different courses of action –desired and undesirable– of the system. This will ultimately facilitate the definition of the strategies, policies and action plans –together with experts and stakeholders– to tackle desertification in the Canary Islands.

The proposed combination of methodologies, as well as the particular implementation sequence aims at allowing a more comprehensive understanding of the case and is thus a more holistic strategy to face the desertification issue. Qualitative and quantitative sources of knowledge are taken into consideration to grasp the different aspects of a social, economic and environmental nature. Thus, the implications of the economic activities carried out in the Canary Islands might be approximated through indicators such as employment rate, GDP, etc. Also, some environmental effects of desertification may be described using quantitative indicators such as the aridity one discussed earlier, but some other characteristics involving the desertification process are best represented using qualitative expressions, mainly the perceptions and opinions expressed by the social actors interviewed during the framing phase. QMs are able to integrate and to structure these different types of information, providing a better understanding of the main driving forces –or leading variables using the QM terminology– that influence the desertification process. However, desertification is an evolving process, so to ascertain how these leading variables and their –either positive or negative– impact influence such a process, a dynamic model was developed based on the framing process carried out.

As a result of both analyses several scenarios were built to aid in the design of a strategy to combat desertification in the Canary Islands. Using the key variables tendencies –proposed by the dynamic model analysis– and the results of the previous QM, within a scenario building approach, this allows us to interconnect tendencies with policy events, creating different likely paths that may help in the definition of courses of actions.

In the following sections, the integrated set of methodologies mentioned above, and the results of its implementation in the assessment of the current and future development of the desertification process will be described.

3.1. The qualitative model

Social systems are very complex and to understand them to make decisions, particularly strategic ones, it is necessary to work

with variables that in the majority of cases are not quantitative. Additionally, even in the case of quantifiable variables, sometimes researchers do not have sufficient information to build econometric relationships among them. These two restrictions may be overcome by the construction of qualitative models, like the one that is presented in this section. It does not give precise relationships between the variables but enables us to understand the structure of the system and to detect the main relationships and roles of the variables.

The general structure of the functions is the following: $Y = f(3X; 1V; 2Z)$. This means that if an independent variable X (or Z) increases (decreases), it will have a positive or negative effect on the dependent variable Y . If there is information that allows us to estimate the magnitude of the effects, the equation may introduce these weights (3, 2 or 1 for instance). In the model that is presented in this section, weights were not used because of the lack of information.

With qualitative models, the precise world of econometric and quantitative models is abandoned and, we are presented with a more imprecise but less reductionist one. In this world, the relationships or equations have to be understood as estimations of the direction (positive or negative) of the change of a dependent variable that is a consequence of a change of an independent one.

The matrice d'impacts croisés-multiplication appliquée à une classification method (MICMAC) was initially developed by Godet (1991a). This method identifies the main variables which are both influential and dependent: those which are essential to the evolution of the assessed system (see, for instance, (Godet 1991a,b; Jouvenel de 1993; Roubelat 1993; Legna Verna, 2005). In MICMAC, the following typology can be distinguished, there are:

- Leading variables, which produce strong impacts on other variables and, to the contrary, are not significantly affected by changes in others.
- Interacting or feedback variables, which produce –directly or indirectly– important impacts on the others and are also affected by their changes;
- Dependent variables, that are the contrary of the first group, because they are very sensitive to the changes of the other variables but do not produce important effects on them; and, finally,
- Variables that may be paid less attention because they neither produce nor receive important effects.

The model was built bearing in mind the following questions:

- What are the main forces –and the feedback between them– leading the the process of desertification?
- What are the main policies that can be applied to these variables and the feedback produced with the aim of improving the quality of life of the population and diminishing the progression of desertification?

With the purpose of providing some insight into these questions, relevant variables were selected after an analysis of the existing literature on the subject and discussion with specialists in the field and relevant public and private social actors. These were selected based on the previous analysis of the *problématique* and the expert consultation process. These actors represent, on the one hand, island and regional public institutions related to areas such as agriculture and livestock, urban and tourism planning and forestry. Together, representatives of the most relevant economic activities (i.e. tourism and agriculture) also participated. They were involved in both the initial phase as well as the final step of discussion of the desertification strategy. The selection process was based on a prior revision of scientific literature, press releases, legal documents and expert consultation.

Thus, the following variables were taken into account in the qualitative analysis of desertification in small islands:

- Degradation of aquifers (aquifers)
- Degradation of biomass and biodiversity (biomass)
- Degradation of quality of irrigation water (irrigwater)
- Increase of construction and road network (infrastruc)
- Increase of desert (desert)
- Increase of land assigned to rural practices that degrade the environment (RPDEland).
- Increase of land assigned to rural practices that protect the environment (RPPEland)
- Increase of population (population)
- Increase of rainfall erosivity (erosivity)
- Increase of tourism (tourism)
- Increase of waste discharges (waste)
- Increase of wind erosivity (wind)
- Increase of soil erodibility (SoilErod)

The variables of the QM may be defined either as stock or flow ones. In the model, they will be considered as flows to emphasize the idea of a desertification process. Additionally, if they are considered as stocks, the state of some variables may be determined by variables that are not relevant for the dynamics of the system, in this case, the desertification process. For instance, the state of the desert, treated as a stock, is determined by, among other variables, the geography of the islands. However, the geography is constant, and its direct effect on the desertification process is not important; though, it may affect the way in which other variables (i.e. wind) impact on the dynamics of the system. But this impact is taken into account in the QM through the effects of “Increase in Wind erosivity (Wind)” and “Increase in Soil erodibility (SoilErod)”.

The matrix in Fig. 2, namely M1, shows the interactions among variables. Cells containing ones (1) mean that the variable located in the row affects the variable in the column, while a cell with zero (0) implies there is no a direct impact between such variables.

Raising matrix M1 to the fourth power allows the detection of indirect impacts among desertification variables. M4, that is, the matrix reflecting M1 is shown in Fig. 2. The analysis of M4 facilitates the disclosure of hidden relationships, which are difficult to understand on the basis of just the information provided by matrix M1.

As an example, the cell in M4 $X^4_{6,4} = 4$ means that the variable in row 6 affects the variable in column 4 four times, that is through three other variables, such as²:

$$V_6 \rightarrow V_A \rightarrow V_B \rightarrow V_C \rightarrow V_4$$

$$V_6 \rightarrow V_D \rightarrow V_C \rightarrow V_F \rightarrow V_4$$

$$V_6 \rightarrow V_T \rightarrow V_G \rightarrow V_M \rightarrow V_4$$

$$V_6 \rightarrow V_J \rightarrow V_B \rightarrow V_K \rightarrow V_4$$

These relationships can be displayed in the form of graphical representation (see Fig. 3), in which the y-axis displays the leading forces (this is calculated based on the sum of rows in M4), while the x-axis shows the dependent ones (the sum of columns). The interaction of these two dimensions divides the diagram into four areas of analysis according to the ability of the variable to influence the rest and the issue. Thus, the leading variables of the system are positioned in the upper left corner, while opposite them, the dependent variables are located in the lower right one. With regard to the interacting variables, these are located in—the upper right hand side while the less important ones for the desertification issue are in the lower left hand area.

	1 : Aquifers	2 : Biomass	3 : IrrigWater	4 : Infrastruc	5 : Desert	6 : RPDEland	7 : RPPEland	8 : Population	9 : Erosivity	10 : Tourism	11 : Waste	12 : Wind	13 : SoilErod
1 : Aquifers	0	0	1	0	1	0	0	0	0	0	0	0	0
2 : Biomass	0	0	0	0	1	0	0	0	0	0	0	0	0
3 : IrrigWater	0	1	0	0	0	0	0	0	0	0	0	0	0
4 : Infrastruc	1	1	0	0	0	0	0	0	0	0	0	0	1
5 : Desert	0	0	0	0	0	0	0	0	0	1	0	0	0
6 : RPDEland	0	1	0	0	0	0	0	0	1	0	1	1	1
7 : RPPEland	0	1	0	0	0	0	0	0	1	0	0	1	1
8 : Population	1	0	0	1	0	0	0	0	0	0	1	0	0
9 : Erosivity	0	0	0	0	1	0	0	0	0	0	0	0	0
10 : Tourism	0	0	0	1	0	0	0	0	0	0	1	0	0
11 : Waste	1	0	1	0	0	0	0	0	0	0	0	0	0
12 : Wind	0	0	0	0	1	0	0	0	0	0	0	0	0
13 : SoilErod	0	0	0	0	1	0	0	0	0	0	0	0	0

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	1 : Aquifers	2 : Biomass	3 : IrrigWater	4 : Infrastruc	5 : Desert	6 : RPDEland	7 : RPPEland	8 : Population	9 : Erosivity	10 : Tourism	11 : Waste	12 : Wind	13 : SoilErod
1 : Aquifers	2	1	1	0	0	0	0	0	0	1	0	0	1
2 : Biomass	2	1	1	0	0	0	0	0	0	0	0	0	1
3 : IrrigWater	0	0	0	1	0	0	0	0	0	0	1	0	0
4 : Infrastruc	0	0	0	3	1	0	0	0	0	0	3	0	0
5 : Desert	0	1	2	0	4	0	0	0	0	0	0	0	0
6 : RPDEland	0	1	0	4	1	0	0	0	0	1	4	0	0
7 : RPPEland	0	0	0	4	0	0	0	0	0	0	4	0	0
8 : Population	0	2	0	1	2	0	0	0	0	4	1	0	0
9 : Erosivity	2	1	1	0	0	0	0	0	0	0	0	0	1
10 : Tourism	0	2	0	0	1	0	0	0	0	4	0	0	0
11 : Waste	0	0	0	1	1	0	0	0	0	1	1	0	0
12 : Wind	2	1	1	0	0	0	0	0	0	0	0	0	1
13 : SoilErod	2	1	1	0	0	0	0	0	0	0	0	0	1

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Fig. 2. (a) Matrix representing direct relationships among variables (M1). (b) Matrix representing direct relationships among variables (M4). (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

From the qualitative analysis, it can be observed that the leading variables of the desertification process are the land assigned to agricultural (both sustainable and non-sustainable) and the evolution of population. The degradation of aquifers, effects on biomass, generation of waste and the water used on irrigation are dependent variables, meaning that those receive the main impacts, which, in turn, produce desertification. With respect to the interacting variables, the role played by desertification and tourism should be emphasized, since they both impact and are affected by the desertification generating a feedback process. These relationships may be appreciated in the following graph (Fig. 4).

The knowledge obtained and structured through the implementation of the qualitative analysis are the main inputs for the system dynamics analysis and the scenarios discussed in the next sections. The way of structuring information obtained as result of this kind of analysis is useful in decision-making processes, since the key policy variables (leading and interacting in the model) are revealed.

3.2. The system dynamics model (SDM)

² For a more detailed explanation on indirect effect see Legna Verna (2005).

³ It was built using VENSIM (vers. PLE plus).

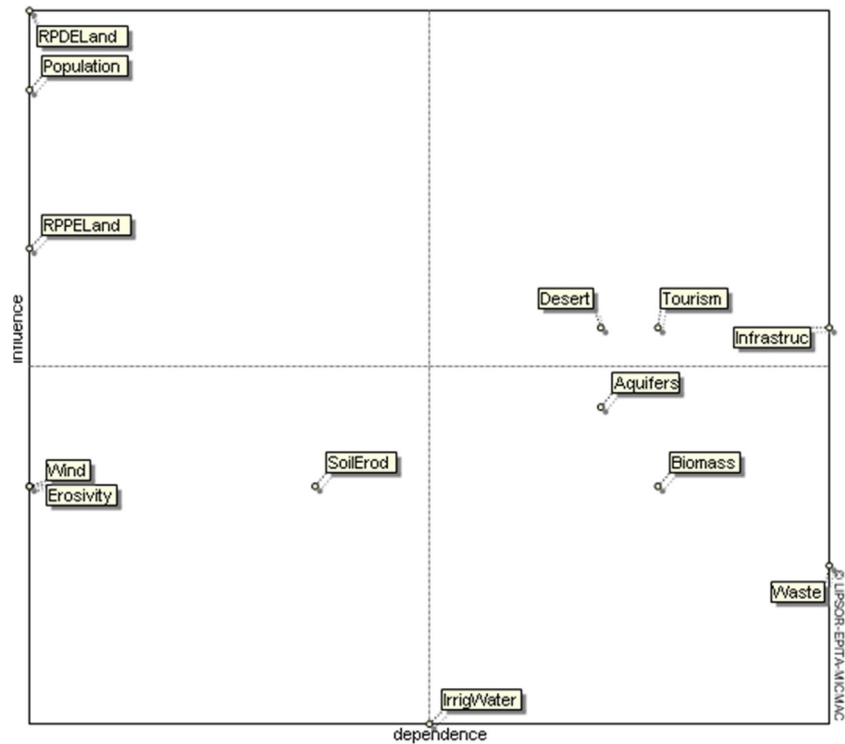


Fig. 3. Indirect influence and dependence map.

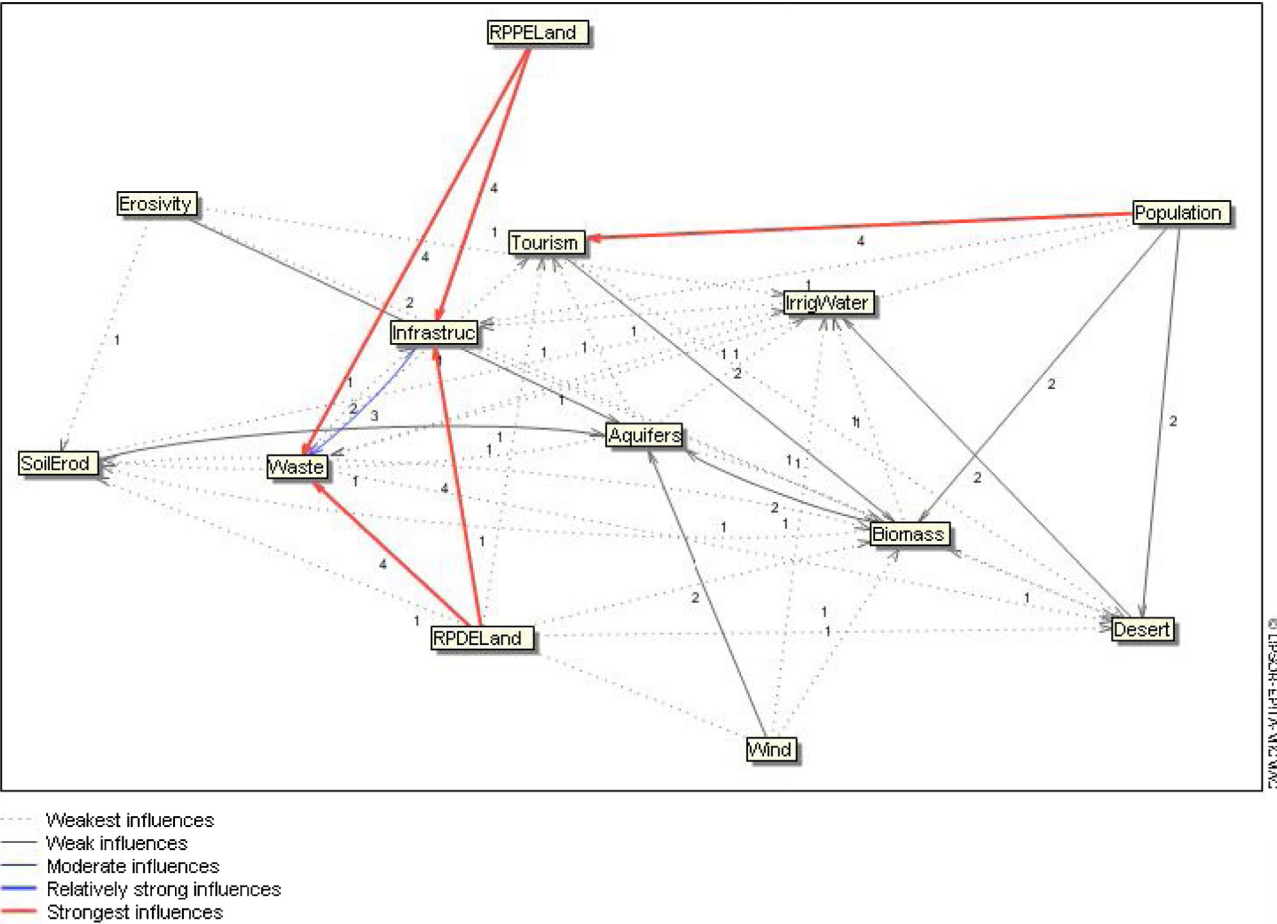
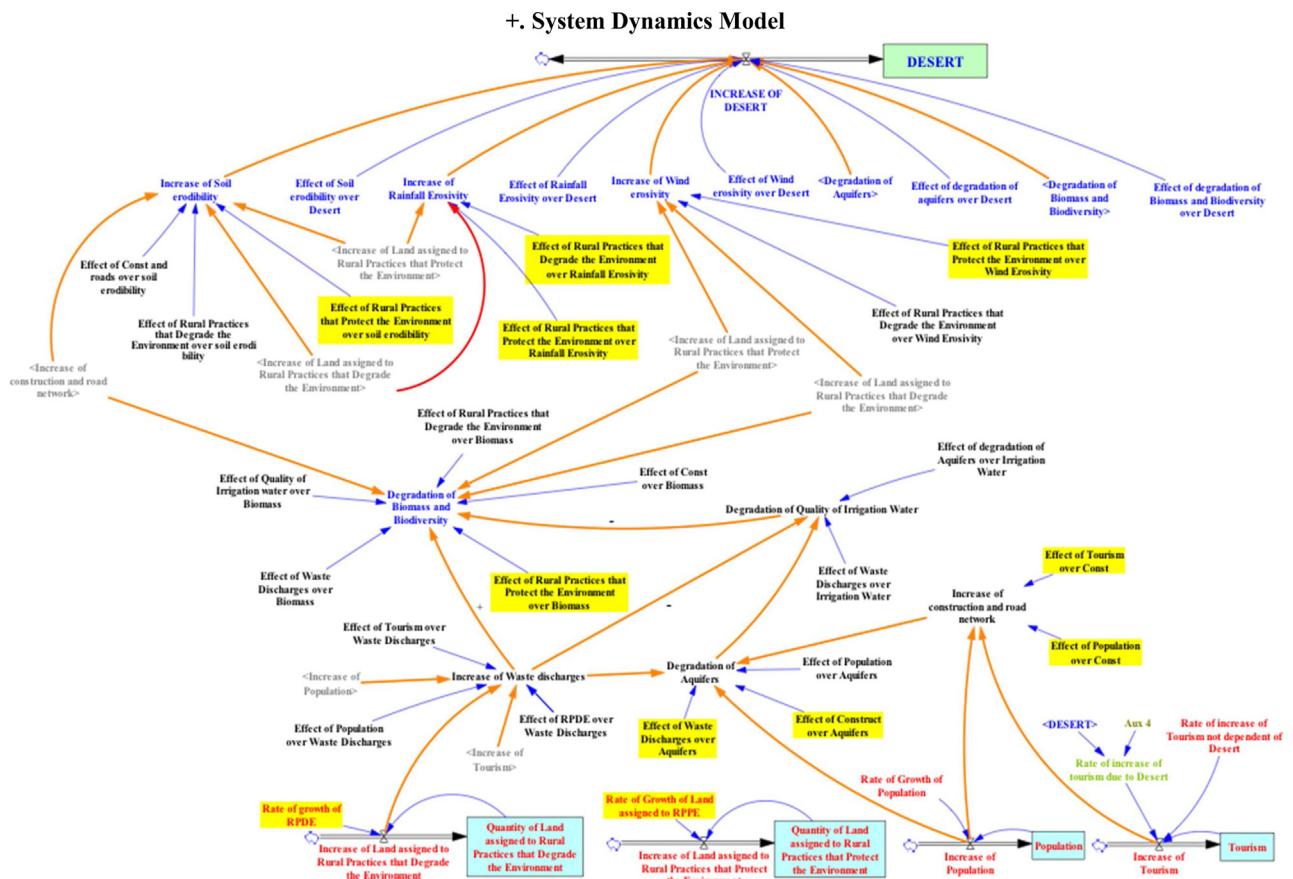


Fig. 4. Indirect influence graph.



Population growth produces a degradation of the aquifers, and increases in waste discharges, construction and road network. Simultaneously, construction of buildings and the road network

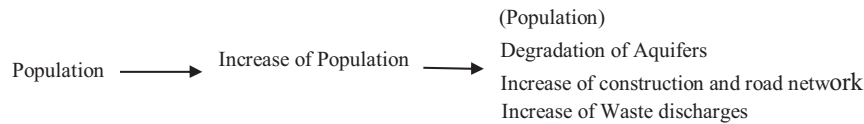


Fig. 7. Variables affected by population.

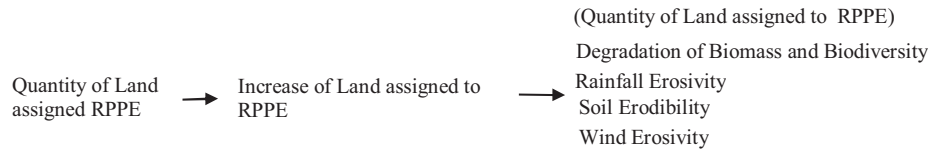


Fig. 8. Variables affected by quantity of land assigned to RPPE.

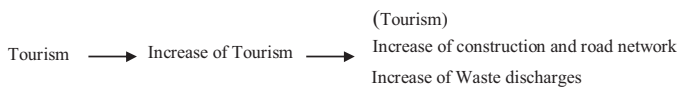


Fig. 9. Variables affected by tourism.

degrade the aquifers, increases soil erodibility, biomass, and biodiversity. Waste discharges have the same impacts on erodibility, biomass, and biodiversity and, in addition, degrade the quality of the irrigation water. These effects are strong, due to the characteristics of the organization of the territory adopted by the Islands. Through the intervention of other variables, they accelerate the desertification.

The majority of tourism products on the Islands are specialized in “sun and sand”, which has produced rapid increases in waste discharge rates, private construction and road network, whose effects have already been commented.

The rate of increase in tourism in the tendency model is an exogenous variable, even though there is an auxiliary variable named “Rate of increase of Tourism due to Desert” (treated as a look up function). This rate is zero in this model, no matter what the level of the desert. This function is changed in the simulation named “Foster Cities & Protected Rural Spaces”, in which, on the contrary, the rate of growth of tourism is affected by the level of the desert (if the level of desert is high, it is negative, see Appendix A). This is because this scenario involves a different category of tourist, who are more interested in the environment.

3.2.2. Using system dynamics to select public policies

Two complementary approaches have been developed to detect policies oriented to reducing the process of desertification: the elaboration of simulations and the analysis of feedback loops.

3.2.2.1. Simulations. Based on the information above, two simulations have been run. The first one was run using the same values of the tendency model. This “Tendency Simulation” (TendS) assumes that the government does not implement active policies to control the processes of desertification and that the social actors will continue their present behavior. A second simulation was run, for the “Foster Cities and Protective Rural Spaces Simulation” (FC&PRS), which on the contrary, assumes that the authorities decide to organize the rural and urban areas in order to improve the environment and to restrain desertification.

The urban areas are called “Foster Cities” bearing in mind the concept of sustainable cities and spaces promoted nowadays by a group of architects, who believe that architects should design and build energy efficient buildings that are sensitive to the cultural and environmental aspects of the location.

Protected rural spaces (PRS) are rural spaces that are organized through a differentiation between the following categories. The

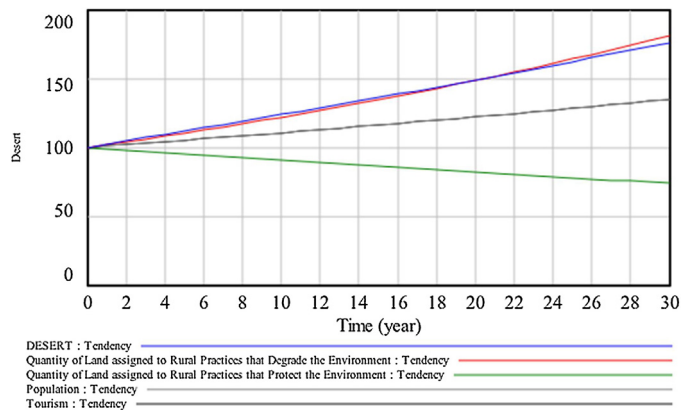


Fig. 10. Evolution in “Tendency” simulation.

first one includes the areas where there are no economic activities, except for a few agricultural activities, which use techniques that do not destroy the environment; they are protected and the population density is low. The second category includes areas where agriculture, some agro-industries and services are allowed, but they use techniques that preserve the environment. The last category includes areas where new agriculture activities will be developed that are capable of not only stopping desertification but of stimulating the recovery of the soil. This is the case of Jatropha, whose production has been initiated in a desert area of the island of Fuerteventura. This scenario includes Foster Cities and Protected Rural Spaces.

The results of the simulations may be observed in Figs. 10 (TendS) and 11 (FC&PRS). The tendency scenario shows that if the behavior of the society goes on as it is at present, the desertification processes will be inexorable. On the contrary, the second simulation shows that these processes may be reversed.

The analysis of the behavior of other variables allows an additional vision of the two scenarios (Figs. 12–15). It may be observed that, although the population, tourism and construction and road network increase, desertification may be controlled in the Canary Islands, if the government implements policies that can move the region away from the bad path (TendS) to the “desired path” (FC&PRS). To generate this evolution, the government should implement policies to change the value of the model variables (the equations and values of the constants are in the Appendix A). In the context of uncertainty and complexity, with a lack of robust quantitative information, the proposed equations were aimed at presenting the directions of the impacts, in order to understand how the variables behave. Thus, SD model results were mainly intended at eliciting possible tendencies and variable linkages.

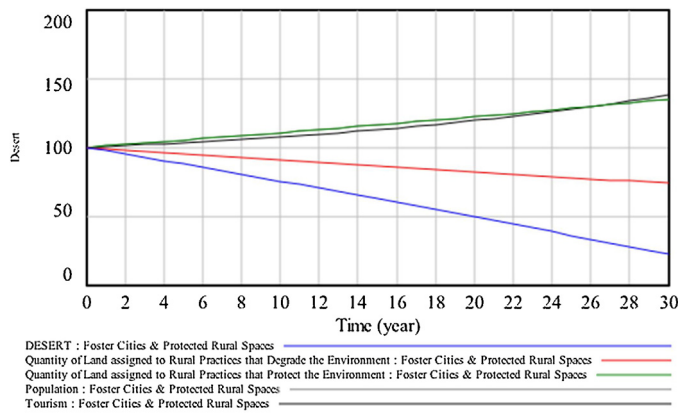


Fig. 11. Evolution in “Foster cities and rural spaces that protect the environment” simulation.

Evidently, this is not possible for all of them. After several discussions and policy analyses, the team concluded that it is possible to implement public policies to modify the following constants (in yellow in Fig. 2a). They have been classified in tree groups: a) effect of population on construction, effect of tourism on construction and effect of construction on aquifers; b) effect of rural practices that degrade the environment on rainfall erosivity; c) effect of rural practices that protect the environment on biomass, effect of rural practices that protect the environment on rainfall erosivity, effect of rural practices that protect the environment on soil erodibility, effect of rural practices that protect the environment on wind erosivity; d) effect of waste discharges on aquifers.

The Canary Islands have experienced a significant increase in population and tourism during the last decades, which, in turn, has produced increases in construction and road network, which has been very destructive for the environment. The FC&PRS scenario aims to reduce this negative impact through policies that concentrate the population and diminish the negative effect of construction on the territory and the impact of the road network on aquifers. These are the constants to be changed (through the policies) in the first group. The second one refers to the rural practices that degrade the environment: the FC&PRS expects to implement policies to reduce the negative impact on rainfall erosivity and its rate of growth. The third group includes constants that refer to the positive impacts of the rural practices that protect the environment and to its rate of growth. The FC&PRS attempts to substitute destructive rural practices with protective ones. In addition, it will attempt to increase the positive impacts. Finally, the desired scenario also foresees the implementation of a policy to reduce the negative effect of waste discharges on aquifers, which in the Canary Islands are very important, due to the scarcity of water.

These results have to be interpreted carefully. They do not intend to provide a quantitative and exact behavior of the variables on the future, but they may indicate a tendency (increase or decrease in desertification). They allow us to understand the structure and behavior of the system and to answer questions like: What will be the effect (positive or negative) on desertification and other variables if the government implements a policy to reduce the effect of the increasing population on the rates of growth in construction and the road network? Is it probable that a set of policies capable of leading the Canary Islands to a scenario “FC&PRS” would revert the tendency of desertification?

3.2.2.2. Feedback loops and selection of policies. The model produces eight endogenous feedback loops (Figs. 16–23) in addition to those produced by the exogenous variables (population, quantity of land assigned to rural practices that degrade the environment and quan-

tity of land assigned to rural practices that protect the environment) and their respective rates of increase. Their polarity is important for the design of policies. The polarity of a feedback loop is the sign (sgn) of the following series (Richardson 1995; Schwaninger and Grösser, 2009):

$$\text{sgn}\{[\delta(\delta x_1/\delta t)/\delta x_n] \times [\delta(\delta x_2/\delta t)/\delta x_1] \times [\delta(\delta x_3/\delta t)/\delta x_2] \times \dots [\delta(\delta x/\delta t)_n/\delta x_{(n-1)}]\}$$

Hence, to be coherent with the previous definition of polarity, this article follows the notation defined by Richardson (1995), distinguishing between positive and negative polarity, which is equivalent to reinforcing and balancing loops, respectively. This approach has been chosen due to the ability of the polarity to change according to the reality that the functions are analyzing. This is relevant since depending on the context, social and economic variables may produce positive or negative impacts (i.e. depending on the tourism rate this economic activity may produce positive or negative social impacts). This possibility of polarity change is taken into account in Richardson’s approach (see Richardson (1995: 5)). Given an increase of “x” in the loop if the resulting effect on the same variable is greater (minor) than the initial increase, the feedback loop will be positive (negative).

This definition of polarity helps us to understand the functioning of the system with respect to the relationships between desertification and tourism and the former’s possible futures. As has been pointed out by Richardson (1995), the sign of the polarity may change. In the tendency model simulation, tourists are indifferent to the size of the desert and so the polarity is positive: if tourism continues to increase due to other causes, regardless of desertification, this process will continue in the future. On the contrary, in the “FC&PRS” simulation, the rate of increase in tourism is positive until a certain level of desert is reached and after this point the rate becomes negative and so does its polarity. In terms of the preferences and characteristics of tourists, it is assumed that the tourists in the two simulations are different. The ones in the FC&PRS simulation are more sensitive to the quality of the environment, while the tourists in the tendency simulation are not. This conclusion underlines the importance of the characteristics of the tourists and the desertification process.

A “core” of sequences that composes the eight feedback loops determines their polarity (see Figs. 16–23). It includes the following sequence: “Increase of Desert → Desert → Rate of Increase of Tourism due to Desert → Increase of Tourism”. The Increase of desert produces an increase of the level “Desert” and this one reduces the Rate of increase of Tourism. As the desert expands, the increase of tourism reduces (in the “FC&PRS” scenario). While this rate is higher than zero, in spite of being reduced because of the increase in desertification, tourism will increase. Nevertheless, there will be a time when the rate of increase in tourism will be zero or low and desertification due to the tourism will be stopped or reduced (tourism is not the only cause of an increase in desert).

However, this situation raises an important political problem because tourism is a vital economic activity in the Canary Islands and must be handled with care. The employment and the revenue generated by tourism means the population greatly depends on it. To be able to maintain tourism without negative impacts on desertification is a key strategic question. The control of the desertification process and the improvement in the environment are economically profitable.

As has been commented, the connections of the core with the other variables produce the eight feedback loops, which have been grouped into two categories in order to draw some conclusions about policies.

1. Core and increase of construction and roads

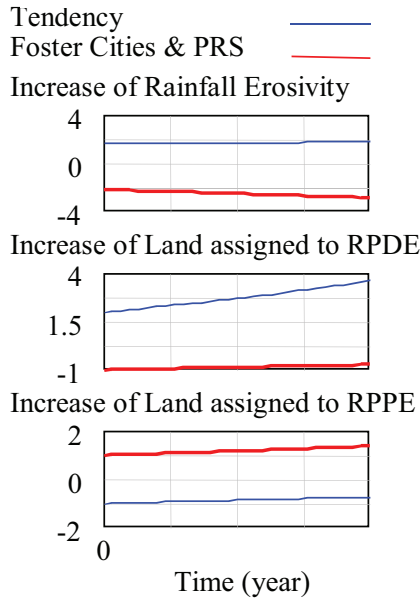
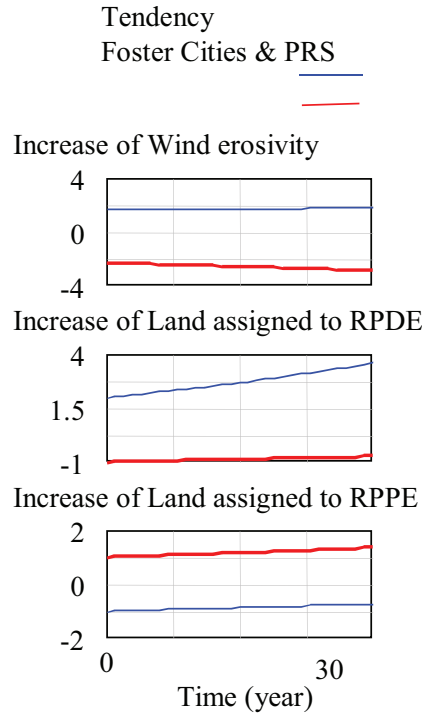
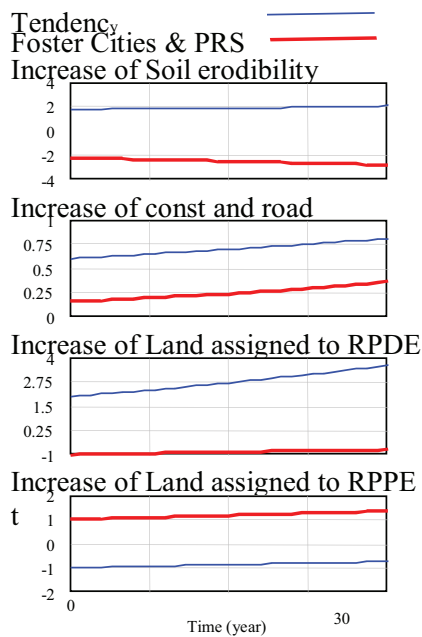
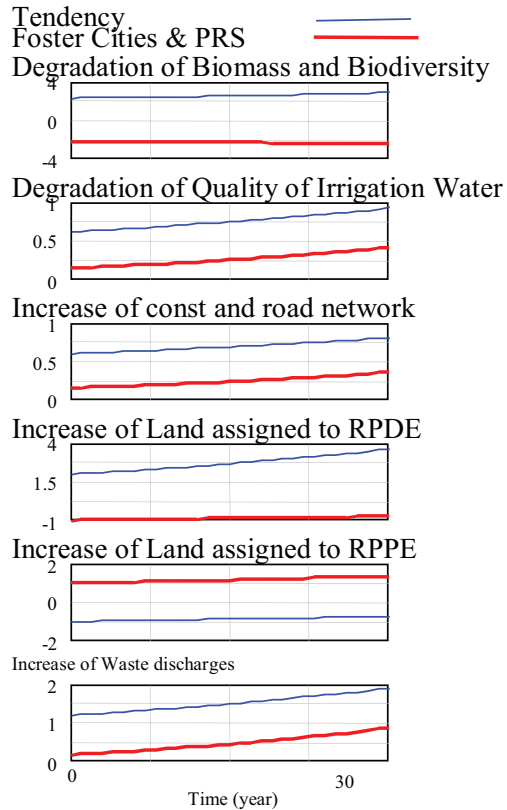
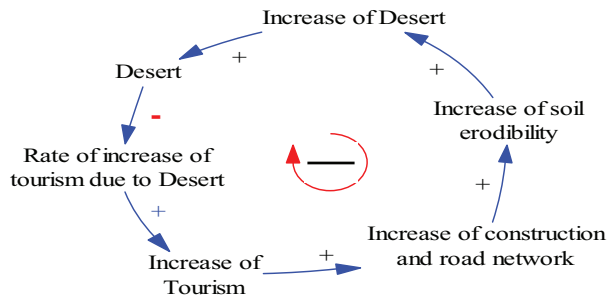
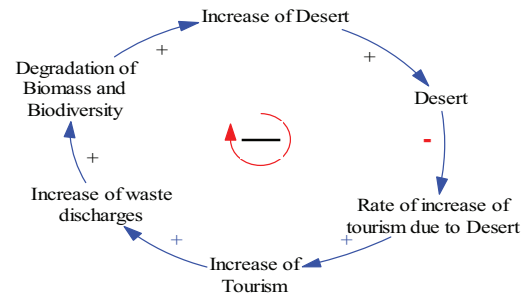
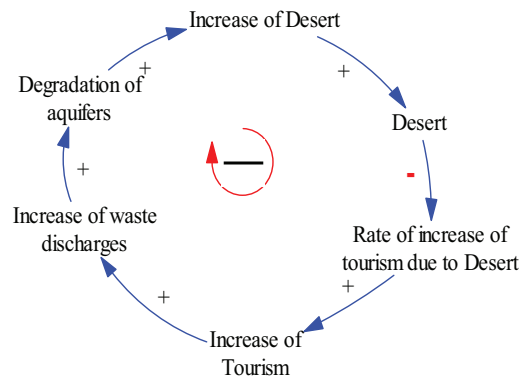
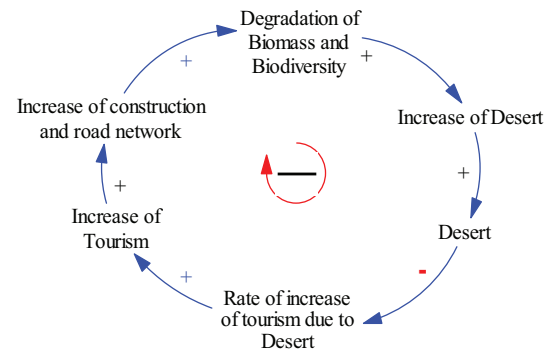
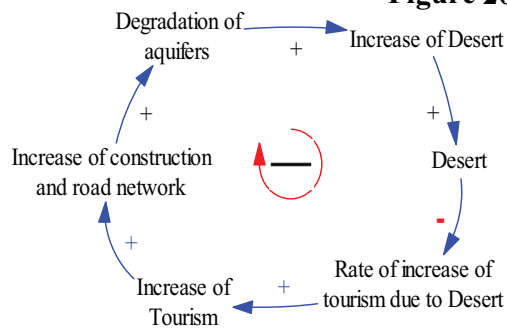
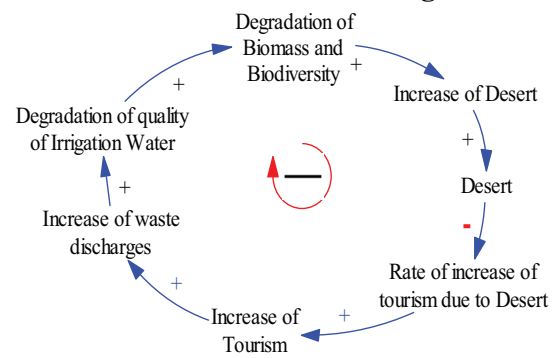
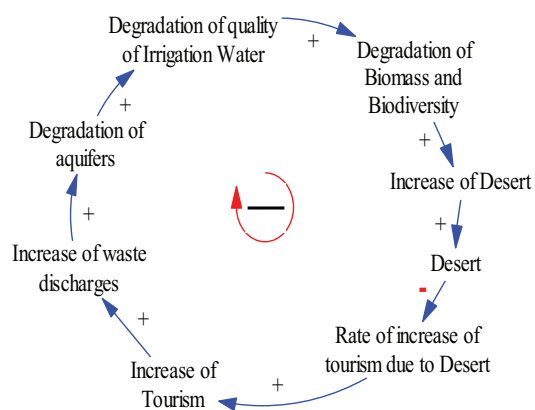
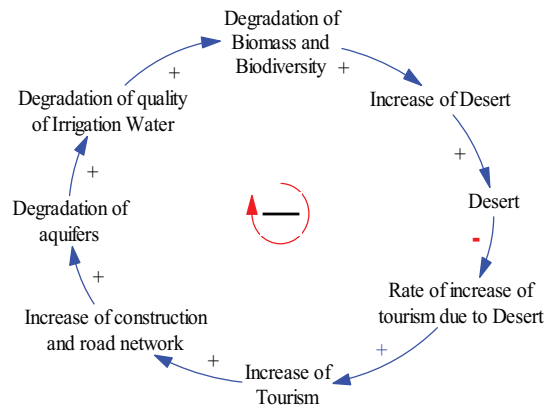
Figure 12**Figure 13****Figure 14****Figure 15****Figs. 12–15.** Behaviour of selected variables of both simulations.

Figure 16.**Figure 17.****Figure 18.****Figure 19.****Figure 20.****Figure 21.****Figure 22.****Figure 23.****Figs. 16–23.** Feedback loops.

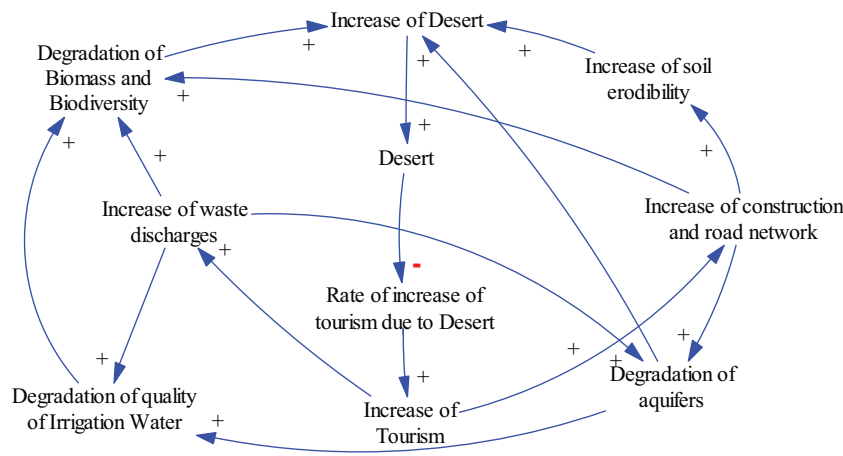


Fig. 24. Integrated causal loop diagram.

- Core → increase of construction and roads → increase of soil erodibility → core (Fig. 16);
- Core → increase of construction and roads → degradation of biomass and biodiversity → core (Fig. 19);
- Core → increase of construction and roads → degradation of aquifers → core (Fig. 20);
- Core → increase of construction and roads → degradation of aquifers → degradation of quality of irrigation water → degradation of biomass and biodiversity → core (Fig. 23);

2. Core and increase of waste discharges

- Core → increase of waste discharges → degradation of biomass and biodiversity → core (Fig. 17);
- Core → increase of waste discharges → degradation of aquifers → core (Fig. 18);
- Core → increase of waste discharges → degradation of quality of irrigation water → degradation of biomass and biodiversity → core (Fig. 21);
- Core → increase of waste discharges → degradation of aquifers → degradation of quality of irrigation water → degradation of biomass and biodiversity → core (Fig. 22).

The causal loop diagram displayed in Fig. 24 represents the integration of the previous causal loops shown in Figs. 16–23)

The two groups reveal the importance of policies in relation to the construction sector and the public infrastructures of transport and management of waste discharges. Regarding the first group, the policies have to reduce the impact of tourism on the magnitude of these two variables and, more importantly, their negative impact on the degradation of biomass and biodiversity and the soil erodibility. As for the second group, the policies have to reduce the increase of waste discharges and they have to be managed to eliminate their negative impacts on the degradation of the aquifers, the quality of the irrigation water and the biomass and biodiversity.

The policies' relationships with the independent variables are evident. An increase in population produces the same consequences on the desertification process as an increase in tourism. The rate of increase of quantity of land assigned to rural practices that degrade the environment has to be reduced drastically, while the rate of quantity of land assigned to rural practices that protect the environment has to be increased.

This set of policies implies a new organization of the territory, combining the Canary Islands' urban system and rural areas. This is

the "Foster Cities and Rural Spaces that Protect the Environment" that is explained in section four.

3.2.3. How variables related to the desertification process were identified and the system dynamics model was built: mental models and validation

Identification of the variables and construction of the models

"People would never send a space ship to the moon without first testing prototype models and making computer simulations of anticipated trajectories.", said Forrester (Forrester 1971, updated 1995). The qualitative and the system dynamics models developed in this paper are prototypes of the real system. They were developed with the intention of being able to stop the desertification processes.

The SDM was built on the base of the QM. The first step was to determine a first set of variables that influence –directly or indirectly– the desertification process in the Canary Islands. The team carried out sessions to exchange ideas to select this set. With this set, a square matrix was built, and then the second step was to establish the functions between the variables (the matrix M1 of Fig. 1). To build the matrix, two kinds of inputs were used: a) the results of research into the desertification process in the Canary Islands; and, b) the mental models of the members of the Team and other actors that were consulted.

Regarding complex problems, there are usually studies that reveal that: "a change in A (increase or decrease) produces a change in B (increase or decrease). For example, a decrease in agricultural practices that protect the environment –like traditional agriculture– produces a degradation of the biomass. Consequently, in matrix M1, the case $X_{7,2}$ is equal to one. It is important to note that our research only allows us to know the direction of the impact between the variables and that it was not possible to establish quantified functions.

The second category of inputs comes from the mental models of the researchers and of other actors consulted, like, for instance, farmers. These models are mental representations of real or imaginary situations (Craik, 1943; Johnson-Laird, 1983) and have been used in system dynamics and system thinking. Returning to Jay Forrester, "Each of us uses models constantly. Every person in private life and in business instinctively uses models for decision-making. The mental images in one's head about one's surroundings are models. One's head does not contain real families, businesses, cities, governments, or countries. One uses selected concepts and relationships to represent real systems" (Forrester 1971, updated 1995). These mental models are a source of very useful information, but it is important to be aware that they are "...fuzzy, incomplete,

and imprecisely stated. Furthermore, within a single individual, mental models change with time, even during the time of a single conversation. The human mind assembles several relationships to fit the context of a discussion, as the debate shifts, so do the mental models. Even when only a single topic is being discussed, each participant in a conversation employs a different mental model to interpret the subject" (Forrester 1971, updated 1995). So, to build the QM, two kinds of mental models have to be distinguished: a) the ones that are in the minds of scientists and that are based on their research and knowledge about the subject; and b) the ones that come from other actors, like farmers, political leaders, etc. The scientific foundations of these second ones were analyzed and "filtered" by the Team. With all this information, matrix M1 was built. It has to be noted that the process is iterative: the matrix was rebuilt several times. Using this matrix the SDM was built. There was no quantitative information to value the parameter affecting its variables; therefore, they were established just to reproduce the estimated evolution of the desertification processes and to allow the simulations to be carried out. This highlights the meaning of the simulations: they only reflect the direction of the effects that produce a change in a variable or a parameter.

The procedure to build the models helps us to appreciate the additional knowledge produced through the design of the SDM. It integrates the spare information and mental models into a model while at the same time making the assumptions and the coherence explicit between them: "By contrast to mental models, system dynamics simulation models are explicit about assumptions and how they interrelate. Any concept that can be clearly described in words can be incorporated in a computer model. The construction of a computer model forces clarification of ideas. Unclear and hidden assumptions are exposed so they may be examined and debated." (Forrester 1971, updated 1995)

3.2.4. Validation of the models

Risbey et al. (2005) argue the "lack of validation data is critical in the case of complex models spanning human and natural systems". Models dealing with socio-environmental complex issues typically require, for instance, socio-economic data, which either have frequently not been collected or are related to value dimensions of problems that are hard to define and quantify.

As commented, the desertification models were elaborated using results from research and mental models as inputs. The validity of a model is its agreement with the real system. The model simplifies the real system, so the criterion to evaluate it is its agreement with reality and if the model can answer the main question: what are the factors that produce desertification?

Karl Popper sustains that theories can never be definitely proved, and they can only reach a greater or lesser level of truth, except in the formal sciences (Popper, 1959; Popper, 1972). All theories are provisional and the principal criterion to assess a theory or a model is falsification. In social sciences, in addition to logical arguments, empirical evidence is a fundamental source to perform falsification. How can falsification be conducted in the case of the desertification models, taking account of the limitation of quantitative information?

"Mental models are akin to architects' models or to physicists' diagrams in that their structure is analogous to the structure of the situation that they represent" (Johnson-Laird and Byrne, 2000).

Thus, to determine the grade of the analogy between the SDM and the reality the authors carried out tests to prove if the mental models and research that are based on the relationships between the variables (a change in A produces a change in B) are false. The results show that they could not be falsified; nevertheless, authors are cautious, because new studies and new mental models can be developed, adding new insights that may lead to improved models.

In addition to the exercise to prove falsehood at the level of the relationships between the variables, another one was conducted at the level of the model, as a holistic representation of the behavior of the reality. A first test showed that the increase of the population and tourism combined with a decrease of the agriculture that protects the environment and the increase of the destructive agriculture is producing desertification. Nevertheless, the team is currently carrying out new research in order to get quantitative information to confirm the validity of the models.

4. The paths of scenarios. Fighting desertification in the canary islands: rethinking strategies through scenarios

The proposed scenarios are a hypothetical sequence of events aimed at focusing attention on causal processes and decision processes. The scenarios were developed on the basis of the results obtained from the previous two analyses. The QM led to eliciting the desertification process' driving forces, while the SDM results showed plausible variable tendencies; together the two scenarios were built to facilitate the later discussion of the *problematique* with the social actors and experts and the design of a strategy to combat the desertification process.

It is relevant to consider scenarios as progressions of events and not as future images. This will help us pay special attention to the unfolding of alternative routes and junctions where human actions can affect the future significantly.

The anatomy of a scenario according to Schwartz (1993, 1996) and Guimarães Pereira and Corral Quintana (2001) encompasses the following elements: a) critical dimensions b) initiative forces, c) strategic invariants (pre-determined elements), d) critical uncertainties and e) discussion (logical, of scenarios) and future image.

Critical dimensions collectively define the multidimensional space where the scenarios can be constructed. They do not necessarily have to represent or contain casual assumptions as they are defined in terms of relevance; they describe the most important attributes of the future images. They are not selected based on their scientific importance, but on the basis of their political value and are used to evaluate the desirability and feasibility of the scenarios.

The following critical dimensions have been defined: a) economy b) society, education and culture, c) science and technology, d) environment and natural resources and e) governability.

Initiative forces (IFs) represent the factors, tendencies or key processes, which may influence the situation or decisions made, as well as those that drive the system and co-determine the unfolding of the future scenario. IFs can be arranged into two main categories: contextual forces: economic, social, environmental processes or events and social actor actions: actions and projects from the government as well as other social and political actors. In the case of the desertification process in the Canary Islands these would be the following:

Economy: a) Competitive economic sectors (agriculture and services), b) public investment (investment into $r + d$), c) private sector investment and d) improvement of the economy.

Society, Education and Culture: a) Integrated civil society and b) environmental education processes.

Science and Technology: a) Infrastructures and b) environmental friendly technologies.

Environment and Natural Resources: a) Access to water, b) pollution processes (i.e. water, atmosphere) and c) Sustainable agricultural production.

Governance: a) Development & land-use planning, and b) institutional stability.

Strategic invariants (predetermined elements) are considered evident and invariant tendencies throughout all scenarios. If an

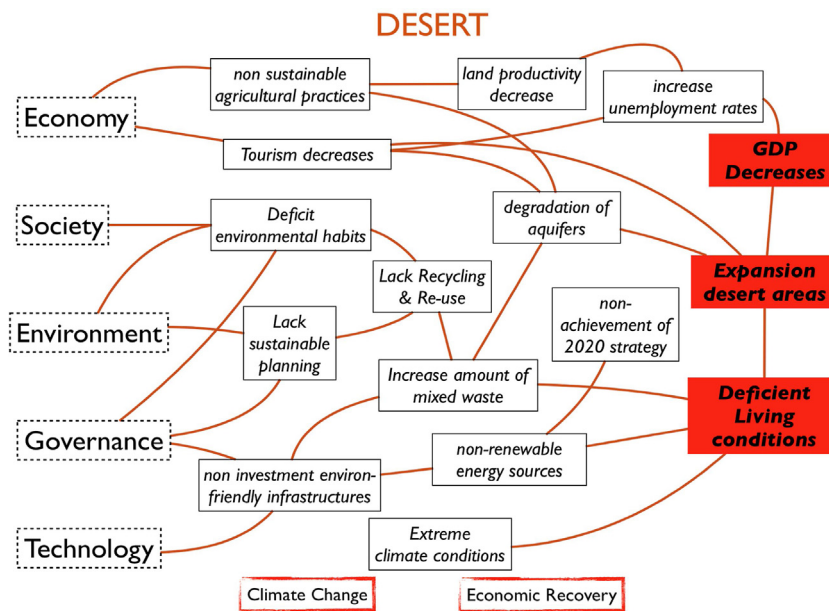


Fig. 25. Representing the temporal interconnections of the desert scenario.

event or a process could presently develop into any scenario, it is a predetermined element. In the case under analysis, the demographic tendency is considered as a strategic invariant.

Critical uncertainties are those initiative forces whose progression cannot be anticipated, but are fundamentally known to affect a set of events, determining principal differences between scenarios.

In the analysis of scenarios for desertification, the following critical uncertainties have been defined: a) Economic recovery and b) climate change.

Scenarios unfold following an internal logic that links the elements into a plot or coherent argument. The challenge is to identify a plot that (1) captures the dynamics of the situation in the best possible way and (2) transmits the meaning of the message effectively. The whole ensemble of initiative forces can develop in different ways, following different plots where eventually, the different elements are combined via a narrative that illustrates how the system evolved from a temporal moment, (generally the present) to a future one.

In this case, two scenarios have been developed aimed at demonstrating different ideas about the Canary Islands within the next 30 years with regards to the desertification process. On the one hand, the named *x* desert scenario, which pretends to narrate a “business as usual” evolution of the Canary Islands, and on the other hand, a positive image represented by the scenario entitled Oasis scenario. Both scenarios are mainly based on the knowledge provided by the qualitative model and the simulations carried out by the dynamic analysis. Thus, in that case the desert scenario reflects the results of the Tendency simulation, while the Oasis scenario corresponds to the Foster Cities simulation.

As mentioned previously, scenarios aim at structuring different types of knowledge (scientific and non-scientific), using narratives to facilitate planning and decision-making processes. Scenarios allow integrating the modeling information together with policy and societal actions and implications providing also a temporal evolution, the whole in the way of narratives, which are an easier way to structure complex patterns and are also more understandable by stakeholders and those concerned (Corral Quintana et al., 2002).

The temporal evolution of both scenarios is shown below. Figs. 25 and 26 represent the interconnections among the different dimensions as well as their evolution over time using a non-linear representation, which is more adequate to deal with reality.

These scenarios were presented in a focus-group session, in which social actors shared their opinions and concerns. In this participatory process, initially the results from QM and SDM were briefly presented to focus afterwards on the presentation and discussion of the developed scenarios. The scenarios were used to facilitate a process of discussion among the involved social actors concerning the characteristics of the desertification issue and possible courses of action. This discussion was a crucial input, together with the results from the previous analyses, to define the Canary Islands’ strategy to fight the desertification process.

5. Policy lessons

Taking into account the outcomes of this integrated approach a holistic strategy to fight the desertification process in the Canary Islands was defined. The Canary Island strategy to combat desertification (CISCOd) was defined with the following three objectives in mind as discussed with social actors:

- The reduction and/or prevention of degradation processes of the areas at risk of desertification,
- Rehabilitation of partly degraded land, and
- Land reclamation of those areas having suffered desertification.

This strategy was structured in six priority areas of action, which were implemented in policies and later in actions involving environmental, social and economic dimensions. The first five axes refer to both sectorial policies, while the sixth is a transverse axis emphasising the need for measures of institutional coordination, as well as in evaluating and monitoring the strategy. The priority action areas proposed by the CISCOd are:

- Priority Axis 1. Land planning and management.

The state of the soil and biodiversity is affected directly and very significantly by the management and techniques used in agriculture, livestock, and forest management. While some of them generate soil degradation processes, there are others that act positively to protect the soil. All these processes are strongly inter-related, for this reason; the Strategy includes the “Priority Axis 1. Planning and Land Management” which contains policies and

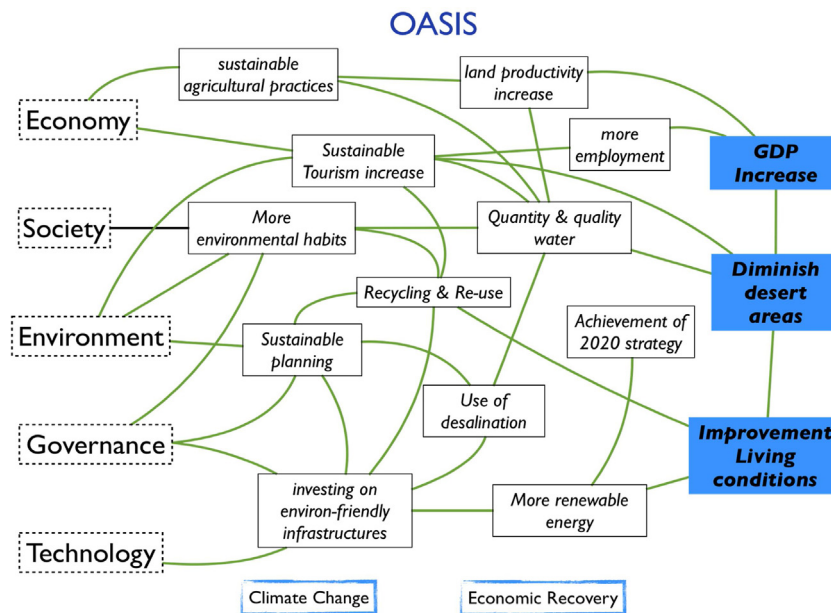


Fig. 26. Representing the temporal interconnections of the Oasis scenario.

actions aimed at guiding the development of agricultural, livestock and forestry activities so that the processes leading to degradation of soils and biodiversity are reversed. Agriculture, livestock and forestry.

– Priority Axis 2. Water planning and management.

A second direct factor of desertification in the Canary Islands is the depletion of aquifers, the quality of existing water and its management for irrigation. The scarcity of this resource, its overuse and misuse are in turn causes of the increasing salinization of some soils, which combined with inadequate agricultural techniques enhance the degradation processes. Reducing the growth of water demand, promoting better use of water and producing it through alternative sources is therefore key to reversing this important cause of desertification. To accomplish this, the growth of crops that have reduced water requirements for their production should be promoted, increasing the efficiency of irrigation systems, together with expanding water production itself and the use of renewable energy.

– Priority Axis 3. Infrastructure, urban planning and waste management.

Transport infrastructure, waste management and urban planning are strongly interrelated. The design of intra and intercity transport infrastructures determine the structure of urban systems of the islands. While waste is generated in farming areas, most of its production and its management are essentially urban activities. The model assessment confirms that these three factors (transport infrastructure, waste management and urban planning) produce significant impacts on the two direct causes of desertification mentioned above. The model adopted for urban development can stimulate dispersion, unnecessary occupation of land, soil sealing and degradation. Depending on the design of infrastructures and cities, and waste management, you can increase or decrease land degradation, biomass and biodiversity and deterioration of aquifers. So the strategy includes this Priority Axis.

– Priority Axis 4. Tourism and trade activities.

Besides the economic activities mentioned in priority axes 1 and 2, other activities also have effects on the environment and desertification in the Canary Islands. Among these, it is important to note the effect generated by tourism, and trade and the services associated with them. These activities require water and energy and generate waste in significant quantities, so the more rational use of these inputs and a better waste management are central to the strategy. Together with the respect for the fragility of the areas in which these activities take place, particularly the fact they are in arid and semi-arid land should be taken into account to contribute to a reduction in desertification in the Canaries.

– Priority Axis 5. Awareness, education and training.

The success of the CISCoD involves the recognition of the existence of a problem of desertification by both social groups and the Administration. This requires the design and implementation of awareness programs in three areas: (a) environmental education both formal and non-formal, (b) training processes to adapt the economic activities carried out in the Canary Islands to the arid conditions, and (c) implement sensitivity programs among social groups addressing the importance of the desertification *problématique* in the Canary Islands. These programs should encourage the dissemination of knowledge and improve governance in relation to desertification.

– Priority Axis 6. Institutional coordination, participation and evaluation system.

As with any strategic plan, coordinated actions among the different institutions and sectors involved is absolutely crucial to make progress toward the desired scenario. Thus, it is necessary to coordinate activities in the following phases: a) the definition of the measures in priority areas and their timing; b) the implementation of measures; c) the evaluation of the results of their implementation; and d) adjusting the plan. Therefore, it is necessary for the Government of the Canary Islands to designate a tier of the administration to be responsible for coordinating the implementation of the actions that make up the priority axes of this strategy, and fundamentally develop the four actions on axis 6.

6. Conclusions

Today's natural resources governance, with multiple criteria and functions and often with multiple social actors with conflicting interests calls for more flexible and versatile decision support than can be gained using "traditional" simulation and optimization tools alone. Generally, in decision-making processes, decision-makers rank a set of decision alternatives and choose the best according to their preferences. According to Kangas and Kangas (2005) however, this is not the best way of approaching complex decision *problématiques*.

The approach proposed in this paper was structured as follows: the first step was the detection of the key variables that affect the problem(s), desertification in the Canary Islands in this case, and the relationships between the variables; that is to say, the building of a qualitative model. The inputs required were the following: research in the field; interviews with specialists and social actors

This step gave a first indication of the variables that should be taken into account to design the system dynamics model, and the scenarios and in which the variables are important to design the policies: the leading and interacting ones. In the case of desertification, this result means that the set of policies to be implemented has to address the following:

- (a) To reduce the rate of increase of the rural practices that degrade the environment and their negative indirect effects; also, to reduce the negative effects of the population⁴; and to stimulate the increase of rural practices that protect the environment and their positive indirect impacts on desertification -working on the leading variables.
- (b) Similarly, in respect to the population, the policies have to reduce the negative effects of the Tourism, which is an interactive variable because the desertification process influences it.
- (c) To foster favorable loops to stop or to revert desertification and to slow down the loops that drive it, focusing on the interacting variables, desert, tourism and construction and road network.

The next step was to build the system dynamics model. Since, it provides an additional point of view to understand the structure of the system that produces the problem or vector of problems (desertification in this example) and to refine the previous conclusions:

- (d) To produce the changes commented in a), the system dynamics model reveals that the policies have to reduce the waste discharges of the rural practices that degrade the environment and their negative impacts on wind erosivity, rainfall erosivity, soil erodibility and, degradation of the biomass and biodiversity. Additionally, policies should improve the favorable effects of the rural practices that protect the environment on the last four variables. The policies might also reduce the effect of the increase of the population on the aquifers, the waste discharges and construction and road network.
- (e) To achieve the desired effect mentioned in b) previously it will be necessary to reduce the effect of Tourism on the increase of Waste Discharges and Construction and Road Network, and
- (f) To reinforce the positive feedback loops.

Next, two simulations regarding the behavior of the system were run using alternative vectors of values as constants. Each of them was associated with a scenario.

- (g) The previous results highlight the variables (including the constant) whose behavior has to be changed throughout the policies to control desertification processes. In addition to them, this new step gives a holistic vision and allows the detection of future scenarios of the system that will be the result of a different set of values of these constants. In turn, each set will be the result of the changes of the behavior of the system produced by the implementation of the policies.

The last step was to build the path and interactions of the variables that lead to the scenarios.

- (h) This step gives another perspective to detect the forces that ought to be fostered or slowed down to move the social system in the desired direction. It emphasizes the links of variables allowing the decision-maker (or those involved in the process) to have an additional holistic view of the issue and its patterns.
- (i) Two scenarios were built in order to facilitate a knowledge sharing process with the different social actors related to the desertification process in the Canary Islands. The use of these scenarios was closely related to the participatory process. Although there was an initial interaction with social actors through direct interviews, a more authentic participation process was carried out at a later stage in the research process. Fifteen public and private institutions representatives participated in the focus group session. It allowed the validation of the results of the previous assessment processes, as the participants were able to explore jointly with the researchers the scope, steps and findings of the applied methodologies in this case study.
- (j) It should also be mentioned that this was the first time in which the different public and private institutions of the Canary Islands were brought together to discuss the *problématique* of desertification. It was a rewarding experience not only for the researchers since it provided valuable knowledge to complement models' results in order to define the strategy and for the participants themselves. As it was clearly stated, the interaction among them enabled opinions to be shared, so they were able to understand their different positions and concerns. Moreover, they also felt part of the process of analyzing the issue and suggesting and discussing actions to tackle it.

As a result of this integrated approach, the Canary Island strategy to combat desertification (CISCOd) was defined. This strategy is currently under implementation by the Regional Government and is aimed at aiding regional and local authorities to take decisions involving uncertain complex systems -also in cases such as the one discussed here in which quantitative data either are not available or are of low quality.

Policy issues cannot be analysed in isolation from the social context in which they occur (Corral Quintana, 2009). Different perceptions, perspectives, opinions, knowledge, and interests bind them. As Lindblom, (1991) argues, there is a deep and persistent unwillingness in Western culture to acknowledge the difficulties arising from the world's complexity and human's modest cognitive abilities, and unless political action is adjusted to take into account the fact that complex problems cannot be understood fully, policy-making will fare much worse than it needs to.

Thus, the emergence of more accountable and inclusive governance styles reject the concept of a single, omnipotent decision maker and replace it with a deliberative process involving extended debate regarding specific policy issues. Moreover, there has also been a progressive recognition that it is not just at the level of decision-making that appropriate consultation, dialogue and deliberation should take place among those concerned with certain governance issues (Corral Quintana et al., 2002).

⁴ Whose rate of increase is not easing to control.

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Appendix A.

Equations and Comparison of the simulations.

(a) Equations of the System Dynamics Model.

(01) Aux 4 = 1.

Units: Desert.

(02) Degradation of aquifers = effect of construct on aquifers $\times$ increase of construction and road network + effect of population on aquifers $\times$ increase of population + effect of waste discharges on aquifers $\times$ increase of waste discharges.

Units: Degradation of aquifers/year.

(03) Degradation of biomass and biodiversity = degradation of quality of irrigation water $\times$ effect of quality of irrigation water on biomass + effect of const on biomass $\times$ increase of construction and road network effect of rural practices that degrade the environment on biomass $\times$ increase of land assigned to rural practices that degrade the environment + effect of rural practices that protect the environment on biomass $\times$ increase of land assigned to rural practices that protect the environment increase of waste discharges $\times$ effect of waste discharges on biomass.

Units: Degradation of biomass and biodiversity/year.

(04) Degradation of quality of irrigation water = degradation of aquifers $\times$ effect of degradation of aquifers on irrigation water + effect of waste discharges on irrigation water $\times$ increase of waste discharges.

Units: Degradation of quality of irrigation water/year.

(05) Desert = integ (increase of desert, 100).

Units: Desert [0,400].

(06) Effect of const and roads on soil erodibility = 0.3.

Units: Soil erodibility/construction and road network.

(07) Effect of const on biomass = 0.3.

Units: Degradation of biomass and biodiversity/construction and road network.

(08) Effect of construct on aquifers = 0.3.

Units: Degradation of aquifers/construction and road network.

(09) Effect of degradation of aquifers on desert = 0.05.

Units: Desert/degradation of aquifers.

(10) Effect of degradation of aquifers on irrigation water = 0.3.

Units: Degradation of quality of irrigation water/degradation of aquifers.

(11) Effect of degradation of biomass and biodiversity on desert = 0.7.

Units: Desert/degradation of biomass and biodiversity.

(12) Effect of population on aquifers = 0.3.

Units: Degradation of aquifers/population density.

(13) Effect of population on const = 0.3.

Units: Construction and road network/population density.

(14) Effect of population on waste discharges = 0.3.

Units: Waste discharges/population density.

(15) Effect of quality of irrigation water on biomass = 0.3

Units: Degradation of biomass and biodiversity/degradation of quality of irrigation water.

(16) Effect of rainfall erosivity on desert = 0.1.

Units: Desert/rainfall erosivity.

(17) Effect of RPDE on waste discharges = 0.3.

Units: Waste discharges/quantity of land assigned to destructive agriculture.

(18) Effect of rural practices that degrade the environment on biomass = 0.3.

Units: Degradation of biomass and biodiversity/quantity of land assigned to destructive agriculture.

(19) Effect of rural practices that degrade the environment on rainfall erosivity = 0.3.

Units: Rainfall erosivity/quantity of land assigned to destructive agriculture.

(20) Effect of rural practices that degrade the environment on soil erodibility = 0.3.

Units: Soil erodibility/quantity of land assigned to destructive agriculture.

(21) Effect of rural practices that degrade the environment on wind erosivity = 0.3.

Units: Wind erosivity/quantity of land assigned to destructive agriculture

(22) Effect of rural practices that protect the environment on biomass = -1.

Units: Degradation of biomass and biodiversity/quantity of land assigned to traditional farming.

(23) Effect of rural practices that protect the environment on rainfall erosivity = -1.

Units: Rainfall erosivity/quantity of land assigned to traditional farming.

(24) Effect of rural practices that protect the environment on soil erodibility = -1.

Units: Soil erodibility/quantity of land assigned to traditional farming.

(25) Effect of rural practices that protect the environment on wind erosivity = -1.

Units: Wind erosivity/quantity of land assigned to traditional farming.

(26) Effect of soil erodibility on desert = 0.1.

Units: Desert/soil erodibility.

(27) Effect of tourism on const = 0.3.

Units: Construction and road network/tourism.

(28) Effect of tourism on waste discharges = 0.3.

Units: Waste discharges/tourism.

(29) Effect of waste discharges on aquifers = 0.3.

Units: Degradation of aquifers/waste discharges.

(30) Effect of waste discharges on biomass = 0.3.

Units: Degradation of biomass and biodiversity/waste discharges.

(31) Effect of waste discharges on irrigation water = 0.3.

Units: Degradation of quality of irrigation water/waste discharges.

(32) Effect of wind erosivity on desert = 0.2.

Units: Desert/wind erosivity.

(33) Final time = 30. The final time for the simulation.

Units: year.

(34) Increase of construction and road network = effect of population on const $\times$ increase of population + effect of tourism on const $\times$ increase of tourism.

Units: Construction and road network/year.

(35) Increase of desert = + degradation of aquifers $\times$ effect of degradation of aquifers on desert + + degradation of biomass and biodiversity $\times$ effect of degradation of biomass and biodiversity on desert + increase of soil erodibility $\times$ effect of soil erodibility on desert + effect of rainfall erosivity on desert $\times$ increase of rainfall erosivity + effect of wind erosivity on desert $\times$ increase of wind erosivity.

Units: Desert/year.

(36) Increase of land assigned to rural practices that degrade the environment = quantity of land assigned to rural practices that degrade the environment $\times$ rate of growth of RPDE.

Units: Quantity of land assigned to destructive agriculture/year.

(37) Increase of land assigned to rural practices that protect the environment = quantity of land assigned to rural practices that protect the environment $\times$ rate of growth of land assigned to RPPE.

Units: Quantity of land assigned to traditional farming/year.

(38) Increase of population = population $\times$ rate of growth of population.

Units: Population density/year.

(39) Increase of rainfall erosivity = effect of rural practices that degrade the environment on rainfall erosivity $\times$ increase of land assigned to rural practices that degrade the environment + effect of rural practices that protect the environment on rainfall erosivity $\times$ increase of land assigned to rural practices that protect the environment.

Units: Rainfall Erosivity/year.

(40) Increase of tourism = (rate of increase of tourism due to desert + rate of increase of tourism not dependent on desert) $\times$ tourism.

Units: Tourism/year.

(41) Increase of waste discharges = effect of rpde over waste discharges $\times$ increase of land assigned to rural practices that degrade the environment + effect of population on waste discharges $\times$ increase of population + effect of tourism on waste discharges $\times$ increase of tourism.

Units: Waste discharges/year.

(42) Increase of wind erosivity = effect of rural practices that degrade the environment on wind erosivity $\times$ increase of land assigned to rural practices that degrade the environment + effect of rural practices that protect the environment on wind erosivity $\times$ increase of land assigned to rural practices that protect the environment.

Units: Wind erosivity/year.

(43) Increase of soil erodibility = effect of const and roads on soil erodibility $\times$ increase of construction and road network + effect of rural practices that degrade the environment on soil erodibility $\times$ increase of land assigned to rural practices that degrade the environment + effect of rural practices that protect the environment on soil erodibility $\times$ increase of land assigned to rural practices that protect the environment.

Units: Soil erodibility/year.

(44) Initial time = 0. The initial time for the simulation.

Units: year.

(45) Population = integ (Increase of Population, 100).

Units: Population density.

(46) Quantity of land assigned to rural practices that degrade the environment = integ (increase of land assigned to rural practices that degrade the environment, 100).

Units: Quantity of land assigned to destructive agriculture.

(47) Quantity of land assigned to rural practices that protect the environment = integ (increase of land assigned to rural practices that protect the environment, 100).

Units: Quantity of land assigned to traditional farming.

(48) Rate of growth of land assigned to RPPE = -0.01.

Units: 1/year.

(49) Rate of growth of population = 0.01.

Units: 1/year.

(50) Rate of growth of RPDE = 0.02.

Units: 1/year.

(51) Rate of increase of tourism due to desert = WITH LOOKUP desert/Aux 4, ([(0,0) - (400,0.04)], (0,0), (400,0)).

Units: 1/year [0,400].

(52) Rate of increase of tourism not dependent on desert = 0.01.

Units: 1/year.

(53) Saveper = time step.

Units: year [0,?] the frequency with which output is stored.

(54) Time step = 1.

Units: year [0,?] the time step for the simulation.

(55) Tourism = integ (increase of tourism, 100).

Units: Tourism.

(b) Constant differences between tendency and Foster cities & protected rural spaces.

Effect of Construct on Aquifers — has changed in value	
0.3	Tendency
0.01	Foster cities & protected rural spaces
Effect of Population on Const — has changed in value	
0.3	Tendency
0.1	Foster cities & protected rural spaces
Effect of rural practices that degrade the environment on rainfall erosivity — has changed in value	
0.3	Tendency
0.2	Foster cities & protected rural spaces
Effect of rural practices that protect the environment on biomass — has changed in value	
-1	Tendency
-2	Foster cities & protected rural spaces
Effect of rural practices that protect the environment on rainfall erosivity — has changed in value	
-1	Tendency
-2	Foster cities & protected rural spaces
Effect of rural practices that protect the environment on soil erodibility — has changed in value	
-1	Tendency
-2	Foster cities & protected rural spaces
Effect of rural practices that protect the environment on wind erosivity — has changed in value	
-1	Tendency
-2	Foster cities & protected rural spaces
Effect of tourism over const — has changed in value	
0.3	Tendency
0.1	Foster cities & protected rural spaces
Effect of waste discharges on aquifers — has changed in value	
0.3	Tendency
0.1	Foster cities & protected rural spaces
Rate of growth of land assigned to RPPE — has changed in value	
-0.01	Tendency
0.01	Foster cities & protected rural spaces
Rate of growth of RPDE — has changed in value	
0.02	Tendency
-0.01	Foster cities & protected rural spaces
Lookup differences between tendency and foster cities & protected rural spaces	
Rate of increase of tourism due to desert — has changed in value	
Tendency	Foster cities & protected rural spaces
X Y	X Y
0 0	0 0.01
400 0	48 0.00289
	95 -0.00368
	150 -0.01
	200 -0.015

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Glossary

- DSS: Decision support systems
 FC&PRS: Foster cities & protected rural spaces scenario
 QM: Qualitative model
 RPDE: Rural practices that degrade the environment
 RPPE: Rural practices that protect the environment
 SD: Strategic decision(s)
 SDM: System dynamics model
 TendS: Tendency scenario
 TIDDD: Tools to informs debates, dialogues and deliberations
 PRS: Protected rural spaces