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ORIGINAL ARTICLE

Numerical model to assess the impact of the strategies to mitigate desertification

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Abstract Desertification is considered a global environmental problem with political and socioeconomic implications. Desertification, exacerbated by climate change, is the largest environmental problem in Chile affecting almost two third of the national territory. This study takes place in a latitudinal gradient of the north-central Chilean drylands, where desertification is a threat to agriculture, livestock and forestry (ALF). In the context of the United Nations Convention to Combat Desertification (UNCCD) and the implementation of the Chilean National Action Programme (NAP), the country is conducting policies and investing in mitigation strategies to combat land degradation and desertification. The main objective of this paper is the development of an integrative methodological approach using real data of the territorial and socioeconomic indicators. With the proposed methodology we assess the impact of the mitigation and land degradation strategies supported by the ALF promotion agencies in the fight against desertification, projecting different scenarios of change. The data were collected in 2008 in Santiago, Chile. The results of the Principal Component Analysis (PCA) suggest that technical irrigation and the improvement of grasslands and pastures play an important role in the fight against desertification. The results of the model projections are consistent, suggesting that the efforts of the ALF promotion agencies have a positive impact in fighting desertification. Inaction of ALF mitigation strategies would increase desertification. This methodological approach, performed with real data, is a contribution for the development of integrative assessments, for replication and for forthcoming discussions.

Keywords Mitigation investments · Atacama Desert · Climate change · Desertification · Dry lands · Indicators · Mitigation strategies · Modeling · Water scarcity

1 Introduction

Desertification and land degradation are composite phenomena that have no single, readily identifiable attribute (Reynolds et al. 2007a). The definition of the desertification is

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controversial and there are more than a hundred different definitions in the scientific literature (Glantz and Orlovsky 1983). The latest definitions have varied in their emphasis on meteorological, ecological and human dimensions of desertification (Geist 2005). Issues such as the process or state nature of desertification, its reversibility, and the relative importance of human vs. climatic causes are subjected to intense arguments (Verón et al. 2006). Human-induced degradation in semi-arid areas is regularly cited as one of the principal causes of desertification (Evans and Geerken 2004). The coexistence of conflicting definitions and divergent estimates, negatively affects societal perception, leading to skepticism and, ultimately, to a delay of eventual solutions (Verón et al. 2006). In this paper we follow the definition given by the UNCCD (1994) that describes desertification as land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities.

Since the publication of the desertification assessments made by Lamprey (1975) in central western Sudan and the introduction of the desert encroachment theory, a variety of estimates, research work and reviews have been published (Rapp et al. 1976; UNEP 1984). Others have questioned these works or have found no evidence for extensive desertification (Hellden 1988; Nelson 1990; Hellden 1991; Tucker et al. 1991; Thomas and Middleton 1994; Nicholson et al. 1998; Prince et al. 1998; Stafford Smith and Reynolds 2002). Nevertheless, as a result of methodological or conceptual problems, desertification assessment remains controversial, and given the potential relevance of desertification, it is surprising that there is no consensus on the proper way to assess it (Verón et al. 2006). However, there is consensus in considering desertification a global environmental problem with political and socioeconomic implications (UNCOD 1977; UNCCD 1994; Yang et al. 2005; Reynolds et al. 2007a). Land degradation does, indeed, have serious consequences for the world's drylands and for some of the most marginal and poverty-stricken societies globally (Gisladottir and Stocking 2005).

It is estimated that 2.6 billion people are affected by land degradation and desertification in more than a hundred countries, influencing over 33% of the earth´s land surface (Adams and Eswaran 2000). Around 73 per cent of rangelands in drylands are currently being degraded, together with 47 per cent of marginal rainfed croplands and a significant percentage of irrigated croplands (Gisladottir and Stocking 2005).

Desertification has a long lasting effect with permanent and sometimes irreversible consequences on production potential, i.e. on the ability of the environment to maintain its long-term productivity (Le Houerou 1996). In that sense the desertification processes, exacerbated by climate change, are a threat to ALF (Lal et al. 2011), and dramatically reduces ecosystem services (Carpenter et al. 2006), being poverty and ecosystem degradation closely associated and exacerbated one another (Biggs et al. 2004). Climate change constitutes an additional pressure that could change or endanger ecosystems and the many goods and services they provide (Gitay et al. 2001, Zilberman et al. 2004). A healthy environment and a sustainable management of resources are essential to develop and maintain the production capacity of the soils (Salinas 2011). Agricultural activity involves a close interaction between the socioeconomic field and the environment. The use of land for agricultural purposes is managed to provide an appropriate and durable production capacity (Meeus et al. 1990).

Most literature on desertification have focused on the assessment of the desertification and land degradation (e.g., Asner and Heidebrecht 2005; Yang et al. 2005; Maestre et al. 2006; Reynolds et al. 2007b; UNESCAP 2007; Requier-Desjardins et al. 2011), on biophysical and socioeconomic indicators to properly assess desertification (e.g., Maestre and Escudero 2009; Nkonya et al. 2011; Sommer et al. 2011; Vogt et al. 2011), on the concept and the contextualization of desertification (e.g., Stafford Smith and Reynolds 2002; Herrmann and Hutchinson 2005 and Reynolds et al. 2007b), and on the evaluation of specific actions such as dune stabilization, tree-screens, shelter-belts, and other works (e.g., Chauhan 2003; Whisenant 1999). The latest published reviews on desertification modeling methods, such as those published by Kapalanga (2008), Grainger (2009) and Reynolds et al. (2011), have shown that much of the work have focused on discussions about setting frameworks.

In that context, many countries are implementing policies and making investments and efforts to mitigate arid land degradation and desertification through the National Action Programmes (NAP), which are one of the key instruments in the implementation of the UNCCD (UNCCD 1994). Our paper proposes the first attempt to develop a methodology using real data of environmental and socioeconomic indicators to assess whether the mitigation and adaptation strategies carried out in the framework of the Chilean NAP, are playing an important role on combating desertification. This paper is a contribution for the development of integrative assessments, for forthcoming discussions, as well as for replication in other areas of the world where other desertification driving forces are taking place or/and other mitigation strategies are being applied.

1.1 Case study

This work took place in a dryland area of Chile, in South America. In Chile the desertification covers 48,334,300 hectares, which represents two thirds of the country (CONAF 1999). Thus, it is considered the largest environmental problem, generating a significant environmental and socioeconomic impact which directly affects more than 1,300,000 people. Poverty, reaches 60.2% of the population in the municipalities most severely affected (INE 2009).

According to the latest agricultural census, the 78% of productive land in Chile, showed degrees of erosion, ranging from moderate to very severe, and in the period 1997–2007, the country has lost 32% of fertile land (INE 2009).

Under future climate and socio-economic pressures, land managers and farmers will be faced with challenges in regard to selecting those mitigation and adaptation strategies that together meet food, fiber and climate policy requirements (Smit and Skinner 2002; Rosenzweig and Tubiello 2007; Fobissie et al. 2008).

Chile has a long history on the control of land degradation and on its effort to mitigate the effects of drought and desertification. However, it was on January of 1998, with the approval and ratification of the United Nations Convention to Combat Desertification and Drought (UNCCD) that the environmental policies for degraded land reclamation started in coordination with diverse national organizations related to this environmental issue.

The Chilean government annually assigns funds to support its main public ALF promotion agencies. The support instruments are the National Irrigation Commission (CNR), National Forestry Corporation (CONAF) and Agriculture and Livestock Service (SAG). These agencies are mainly responsible for promoting forestry, agriculture and livestock in the country and for preserving the natural resources in areas where these activities take place.

Thus, CONAF, through its Decree Law No. 701 on forestry development includes the reforestation of lands for the purpose of encouraging the recovery of degraded forest lands. SAG through Supreme Decree No. 202 incorporates the recovery of soils in agricultural use of land through conservation, reclamation and rehabilitation. Similarly Law No. 18,450 of the CNR aims to increase the irrigated area of the country by encouraging the irrigation of dry land, and by incorporating new land to farming.

1.2 Objectives

The main objective of this paper is to develop a methodological approach to evaluate the impact of the strategies used to combating desertification, using real data of territorial and socioeconomic indicators. The specific objectives are: to assess whether the financial assistance provided by the ALF promotion agencies is helping to mitigate desertification; to identify the main causes of human-induced desertification; to identify the most effective mitigation strategies; and to foresee simulation scenarios in relation to increased action and inaction by the ALF promotion agencies.

2 Material and methods

2.1 Area of study

This work takes place in north-central Chile, between latitudes 17º 30′S and 36º 33′S. The areas between these latitudes are the administrative regions affected to greater erosion and drought in the country. The total surface area of study is 37,935,970 ha, representing 50.2% of the country. Thus, the first four regions under study (Regions XV, I, II and III) have almost total absence of rainfall and extremely dry conditions of the environment. The average annual temperature is between 17º–18°C. Precipitation in the Region IV is relatively low, approximately 150 mm/year and the average temperature during the winter months is 14º C. In the last three regions under study the climatic conditions are better. Thus in the Regions V, VI and VII the precipitation is about 340 to 700 mm/year and the winter average temperature is 13.5°C (INE 2009).

In relation to the use of land in the northernmost regions, i.e. Regions XV, I and II, there is a high percentage of land devoid of vegetation. This percentage is about 75% and only a 23% corresponds to grassland and shrub lands. The percentage of agricultural land in these regions is about 0.5% (INE 2009). In the next two regions, i.e. Regions III and IV, the area devoid of vegetation is 38% and 59% respectively. The percentage of agricultural land is about 2.3% (INE 2009).

The use of land in the southern regions presents another situation. The percentage devoid of vegetation is of 18%. Around 20 to 25% of the use of land is devoted to the forestry and agricultural activities (INE 2009). The Fig. 1 shows the area of study.

2.2 Study indicators

The basis for the assessment carried out in this work is the selection of territorial and socioeconomic indicators with descriptive and predictive ability. The selection of the territorial and socioeconomic variables was performed by reference to the indicators recognized by the UNCCD. These indicators include: level of land degradation, water capacity or availability, changes in the use of land, population in areas affected by desertification, poverty and human development index. The selection of variables also depended heavily on the availability of the data in the files of the public administrations.

The selected territorial indicators characterize the area of study. An important criterion for the selection of these indicators was to take into account that they are directly related to human activities in the territory. The descriptors that do not depend on human activity, such as lithological, meteorological or geomorphological variables, were not directly considered in this study. The selected socioeconomic indicators are those related to the production structure of the territory, to rates of poverty and human development, to infrastructure and to

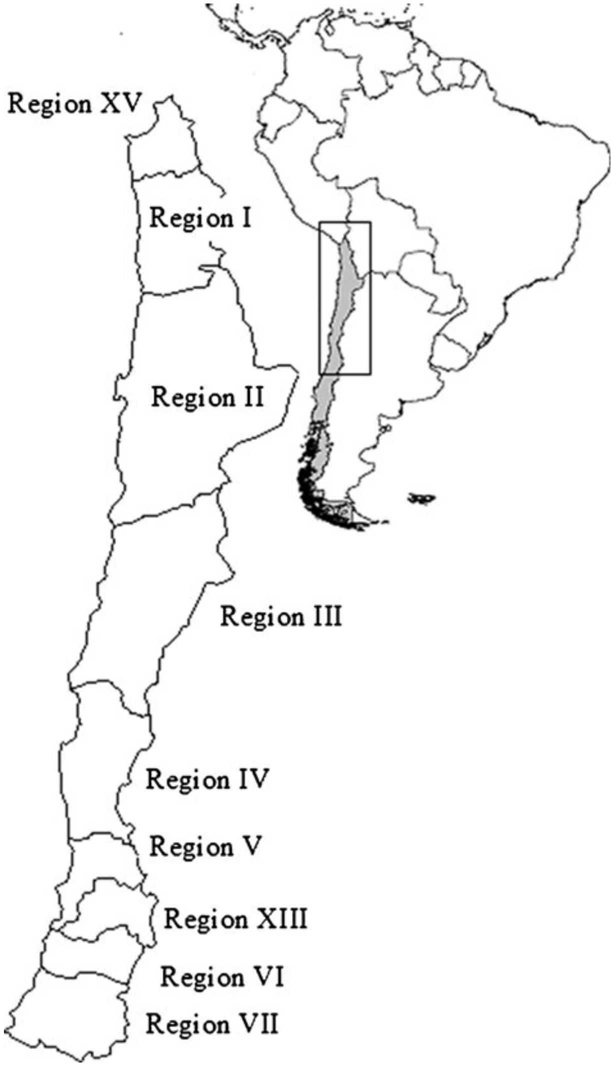

Fig. 1 Map of the area of study showing the administrative regions considered to carry out this work

the financial support given by the ALF promotion agencies to conduct land reclamation and mitigation strategies.

The data were collected in 2008 in Santiago, Chile, from the databases of CONAF, SAG, CNR, the National Institute of Statistics (INE), and the National Socioeconomic Characterization Surveys (CASEN). They were arranged in two groups that describe the regions analyzed across 19 territorial indicators and 15 socioeconomic indicators. Table 1 shows the descriptors used.

According to Reynolds et al. (2007a), obtaining accurate estimates of the amount of drylands affected by desertification is a difficult task, fraught with numerous obstacles and complications, and in that sense, this work is not an exception. We assume that the areas affected by desertification are those given in the Chilean map of desertification carried out by CONAF (1999) in the context of the implementation of the NAP in Chile (PAN 2000).

Table 1 List of the socioeconomic and the territorial indicators considered for this study

Socioeconomic indicators	Territorial indicators (ha)
CNR's total investment (U.S.$)	Surface operated by the CNR (ha)
SAG's total investment (U.S.$)	Tech Surface by the CNR (ha)
CONAF's total investment in (U.S.$)	New irrigation surface CNR (ha)
Total population (Number of inhabitants)	Surface operated by the SAG (ha)
Poor population (Number of people)	Surface operated by CONAF (ha)
Non-poor population (Number of people)	Surface in severe condition of desertification (ha)
Number of vehicles (Number)	Surface in moderate condition of desertification (ha)
Employed population (Number of people)	Surface in slight condition of desertification (ha)
Unemployed population (Number of people)	Surface not affected by desertification (ha)
Number of farms (Number)	Surface without information about its condition of desertification (ha)
Cattle heads (Number)	Surface occupied by annual crops (ha)
Forest fires (Number)	Surface occupied by sown pastures (ha)
Overgrazing (Number of goats and sheep)	Surface occupied by fallow (ha)
Population employed in agriculture (Number of people)	Surface occupied by prairies (ha)
Water reservoir capacity (m^3)	Surface occupied by rangeland (ha)
	Surface occupied by forest plantations (ha)
	Surface occupied by native forests (ha)
	Surface occupied by infrastructure (ha)
	Surface occupied by barren land (ha)

2.3 Model development

The performance of simple models helps us to understand the interactions that may exist in more complex models (Murray 2001). Our work takes as reference the model used by Schmitz et al. (2003) to determine the dependence between landscape typology and the socioeconomic structure in cultural landscapes, resulting in a new concept of this methodology. Our model considers the relationship between the territorial and the socioeconomic indicators trying methodological approaches based on their descriptive and predictive capacity. The proposed methodological approach of our paper allows us to assess whether the mitigation strategies conducted by the ALF promotion agencies are taking effect in combating desertification and at the same time to get an overview of the factors affecting the desertification process in the northern regions of Chile. Finally, this methodology allows us an approach to future scenarios of change.

The administrative regions were considered as the units of analysis, being the socioeconomic and territorial information registered to further development of the model which relates the socioeconomic indicators and the territorial structure associated to desertification. The territorial indicators were used as the independent variable and the socioeconomic indicators were used as dependent variables.

Prior to the statistical analysis, a standardization of the data (α) was made. The data were homogenized in relation to the total surface of the region to which they belonged, and then were subjected to logarithmic transformation ($\log(\alpha+1)$), to homogenize the variance of the data (Jorgensen 1993).

On a first step, a Principal Component Analysis (PCA) to the territorial variables and an ordination of the regions in two axes (x, y) was carried out, in order to determine the main territorial components of the desertification.

The selection of the components on the PCA analysis was made so that the first component picked up the greatest proportion of the original variance. The second component collected the maximum variance not collected by the first, and so on. We selected the first two components because together they explained most of the total variance. These were called principal components (Baro and Alemany 2000).

Once selected the territorial variables, a relationship between the type of land and the socioeconomic structure in the area of study is established using multiple regression analysis (Margaleff 1998). The independent variables were socioeconomic descriptors of the regions and the dependent variables corresponded to the territorial variables previously selected in the PCA analysis. Multiple regression analysis provides our model the relation between the regional variables and the socioeconomic structure. By using this method we get a model with a limited number of socioeconomic variables.

The obtained model describes the degree of impact of socioeconomic variables on the desertification. This equation was used to simulate two different scenarios of change. The first one is extrapolating a situation to help reversing the desertification process, i.e. an action scenario, and the other projection is to extrapolate a situation of no financial support given by the ALF promotion agencies, i.e. an inaction scenario. The restrictions of the model were associated to the risks described by (Pukkala 1998; Schmitz et al. 2003).

3 Results and discussion

3.1 Analysis of the territorial variables of desertification

The PCA applied to the 19 territorial variables suggests that the two first components explained the 75.36 % of the variance; Component 1 explained the 60.03 % and Component 2 explained the 13.34 %. Thus, both components reflected most of the variation range of desertification, explaining as a whole from severe and moderate conditions to slight or even no desertification conditions.

As mentioned above Component 1 explained 62.03 % of the total variance. According to the PCA analysis, the Component 1 has a positive maximum value of 0.984 for the CNR Surface of New Irrigation. The maximum negative value is −0.551 represented by the Surface Severely Affected by Desertification. These extremes values characterized the desertification gradient, where the negative extreme suggests a situation of severe condition in relation to desertification, and the positive extreme suggests a degree of less desertification.

Table 2 shows the gradient of desertification for the Component 1 obtained from the territorial variables introduced in the PCA. In the negative extreme we considered the Surfaces Affected by Severe and Moderate Desertification indicators, which have values closer to −1. For the groupe of the variables in the positive extreme, we considered the values closer to 1. This range of values included the surface intervened by the ALF promotion agencies. These areas, located in the positive extreme would represent areas with the lowest degree of desertification.

The result suggests that the ALF promotion agencies would be helping to mitigate desertification through their mitigation and land reclamation strategies. In the case of the CNR this fact is shown by the increase of areas devoted to new irrigation and technical irrigation. In the case of SAG, the recovery of degraded soils seems to be a key factor, and in the case of CONAF the expanding criteria for reforestation by the incorporation of smallholders to forestry plans or degraded land reclamation seem to play a key role too. Therefore,

Table 2 Desertification gradient obtained from the PCA for Component 1. The gradient suggests a movement from a situation of moderate to severe desertification degree, to a degree of less desertification, dominated by areas intervened by the ALF promotion agencies

Component 1 (62,03 % of the variance)	
Severe desertification mitigation gradient	
−	→ +
Severe desertification (-0,55)	New irrigation surface CNR (0,99)
Moderate desertification (-0,42)	Technical irrigation surface by the CNR (0,98)
	Surface occupied by improved grasslands (0,93)
	Surface occupied by annual crops (0,93)
	Surface occupied by forest plantations (0,92)
	Surface intervened by the SAG (0,92)
	Surface occupied by native forests (0,90)
	Surface intervened by CONAF (0,90)
	Surface intervened by the CNR (0,864)
	Surface occupied by sown pastures (0,864)

List of indicators of greatest loadings in the characterization of the Component 1 and interpretation of the variation tendencies that they represent. The values obtained in the PCA are shown in parentheses

the gradient of desertification developed by PCA suggests the relevance of the three ALF promotion agencies in the fight against desertification and drought.

Component 2 explained 13.34% of the total variance and suggests territorial variables that are associated to areas not affected by desertification, and in a lesser extent to areas with a lower degree of desertification. On its positive extreme, the maximum value is 0.65 for the Area Not Affected by Desertification and the negative extreme value is −0.70 for the Rangelands.

Table 3 shows the gradient of desertification for the Component 2. In the negative extreme we considered the maximum values obtained by the PCA analysis. These values are Sown Pastures, Fallows and Rangelands. In the positive extreme we found the indicator Surface Not Affected by Desertification and areas representing less desertification, such as Surface in Slight and Moderate Condition of Desertification.

As mentioned above, the Component 2 suggests a desertification gradient of lesser extent. The territorial variables associated with this lesser degree of desertification are mainly Rangelands, Sown Pastures and Fallows. These variables suggest the activities of the ALF promotion agencies analyzed. In the case of land devoted to fallow, fallow work helps keep the land in a better status of preservation and prepares it for new plantings, usually for annual pastures.

In order to analyze the situation of the regions studied in relation to the desertification gradients, we represented the position of the regions in two axes. The Fig. 2 shows the graphical representation of the studied regions in relation to the indicators values obtained in the PCA analysis for Components 1 and 2. Both components explained the 75% of the total variance. The main result of this analysis is that the position of Regions VI and VII suggests a better condition in relation to land degradation in relation to the other regions. The relatively high values in terms of the Components 1 and 2 for the Regions VI and VII, suggest large areas intervened by CONAF, SAG and CNR.

3.2 Impact of the ALF promotion investments and the socioeconomic structure on desertification

The relation between desertification and socioeconomic structure was determined by a model, where the area affected by severe and moderate desertification was introduced as the dependent variable. The socioeconomic indicators, including the financial support

Table 3 Desertification gradient obtained from the PCA for the Component 2. The gradient suggests a strengthening of the areas occupied by shown pastures, fallows and rangelands, to a degree of less desertification and even to a status of no desertification

Component 2 (13,34 % of the variance)	
Slight desertification mitigation gradient	
–	→ +
Surf oc. by sown pastures (-0,46)	Surf. not affected by desertification (0,65)
Surf. oc. by fallows (-0,657)	Surf. in slight condition of desertification (0,47)
Surf. oc. by rangeland (-0,7)	Surf. in moderate condition of desertification (0,46)

List of indicators of greatest loadings in the characterization of the Component 2 and interpretation of the variation tendencies that they represent. The values obtained in the PCA are shown in parentheses

provided by the ALF promotion agencies to deploy mitigation strategies, were entered as independent variables. All the predictive indicators introduced in this model were: the Capacity of Water Reservoirs, Total Population, Overgrazing, the investments of CNR, CONAF and SAG, and the Total Number of Farms. The result obtained is as follows:

$$Desertification = 0.269 - 0.021\, CONAF's\, Investments - 0.08\, CNR's\, Investments - 0.632\, SAG's\, Investments + 1.331\, Total\, Population - 0.218\, Number\, of\, Farms + 3.386\, Overgrazing - 0.008\, Water\, Reservoir\, Capacity$$

This result suggests that the indicators which imply a decline of desertification are the mitigation investments of CNR, SAG and CONAF, the Number of Farms, and the Capacity of Water Reservoirs, which indicate a mitigating role of the ALF promotion agencies. On the other hand, the indicators that lead to an increase of desertification are Overgrazing and the Total Population. This result suggests that the investments of the CNR, CONAF and SAG play an important role on the adaptation and mitigation of desertification and draught.

In relation to the enforcement of the modern irrigation, our results are consistent with those found by Zou et al. (2011) for China. The study of these authors showed that water saving irrigation (WSI) can serve as a useful enabler in dealing with climate change.

In the case of SAG the investments are related to management issues in arid soils and to livestock management (Quezada et al. 2008). Desertification tends to be associated with land degradation in rangelands; however, desertification combines many land degradation pro-

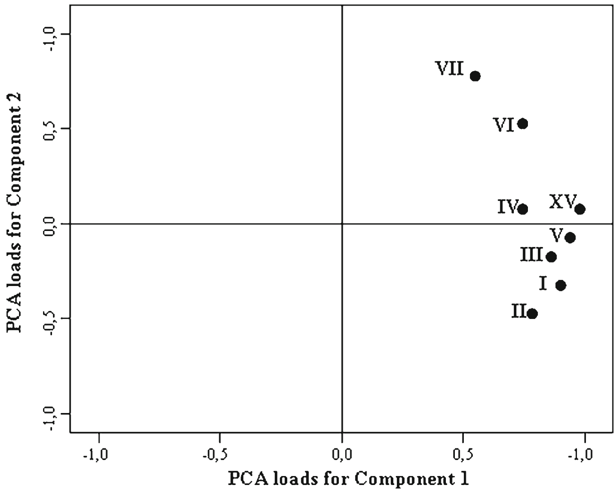

Fig. 2 Graphical representation of the studied regions in relation to the values obtained by each one for the Component 1 and Component 2

cesses and can be exacerbated by climate change (Gitay et al. 2001). In that sense, the mitigation investments made by SAG to preserve and to improve soils in rangelands, seem to be effective in combating desertification.

Our results indicate that Overgrazing is the most important desertification driving force. In our model this result is very important and revealing, because it suggests the validity of our methodological approach. It is well known that overgrazing is one of the driving forces of desertification around the globe (FAO 1964; Huss 1972; Le Houérou 1981; Grainger 1990). The erosive impact caused by goats and sheeps is not only associated with the arid lands, but it also affects the Andean plateau pastures used as summer pastures (Quiroz 2007).

The specific biophysical consequences of desertification differ substantially between geographical areas of the globe as a function of the intensity and number of driving forces at work, the extent of the impacted area, the duration of the deterioration, and the resilience of the system components, especially vegetation (Reynolds et al. 2007a). A way to reduce the impact of overgrazing and to encourage sustainable economic activity, could be to incentive and promote the breeding and marketing of llamas and alpacas for meat and wool. These camelids are the native livestock of the studied regions. Grazing of this type of livestock, especially in the Andean plateau wetlands, does not cause erosion or damage of the soil. This is mainly due to their way of feeding, that contrarily to the goats; their hoof pads do not damage the soil.

The Total Population indicator provides data on the pressure it exerts on the environment. Thus, areas with higher population density are associated with an increased degradation of the soil resources (EEA 2002). According to the last census, the population of these regions is concentrated in the provincial capitals and mayor cities due to the migration from rural to urban areas (INE 2002; FAO 2009). This situation leads to abandonment of rural land, which under drought conditions is at high risk of desertification (Zelaya 2010). There is also a negative effect on employment opportunities, economic growth and the quality of life of rural areas (Correia 1993). This fact agrees with UNCCD (2004), which describes a cycle associated to desertification, poverty and natural resources degradation in the regions socioeconomically most depressed. In that sense it could be relevant to promote economic sustainable activities in rural areas, in order to support the homogeneous distribution of the population.

The Reservoir Capacity is a key indicator that refers to water resources and its availability. The establishment of water resource management policies allows the land reclamation by technical irrigation, sustainable agriculture and forestry to mitigate desertification and drought. In the past years, the number and capacity of the reservoirs has increased. In Region IV, two new reservoirs have been built, Puclaro and Corrales.

In Chile, an agent known to cause soil erosion and desertification is forest fires (CONAF 1999). However, this study has not proved that forest fires are a significant driver of desertification in the studied regions.

3.3 Action-inaction scenarios associated to desertification changes

The obtained model was used to simulate two different scenarios. In the first one we projected a scenario assuming an increase in the percentage of the ALF promotion agencies contribution, and assuming changes in the other variables as indicated in Table 4.

We considered a low rate on the increase of the investments made by SAG, CONAF and the CNR in the northernmost Regions XV, I and II, because we assumed that there is an intrinsic limiting condition of aridity in these regions. In Regions III, IV and V, we assumed a higher increase in the investments of these three ALF promotion agencies due to the high

Table 4 Percentage of variation applied to the baseline situation used in the projected simulation of an increasing action by the promotion agencies

Region	CNR investments	SAG investments	CONAF investments	Farms	Total population	Water reservoir capacity	Overgrazing
I	25%	25%	25%	20%	1,10%	25%	−50%
II	25%	25%	25%	20%	1,10%	25%	−50%
III	50%	50%	50%	20%	1,10%	25%	−50%
IV	50%	50%	50%	20%	1,10%	50%	−50%
V	50%	50%	50%	20%	1,10%	25%	−50%
VI	15%	15%	15%	20%	1,10%	25%	−50%
VII	15%	15%	15%	20%	1,10%	25%	−50%
XV	25%	50%	0%	20%	1,10%	25%	−50%

rates of desertification, and taking into consideration that the arid conditions are not as extreme as in the group of the northernmost regions. In Regions VI and VII, the considered increase of investments was smaller (15%) than in other regions because in these regions there is a lower rate of desertification and they have a high development of the ALF sector. These regions have a higher annual rainfall compared to the other studied regions. We have steadily declined the Overgrazing indicator in all regions. The increase in the Total Population was considered in relation to the population projections given in the last national census conducted by INE (2002). The significant increase in the Capacity of Water Reservoirs was conducted in a uniform way for all regions except for Region IV. Figure 3 suggests that an increased action scenario significantly reduces desertification.

The simulation suggests a decrease of the desertification, mainly in Regions IV and V. The result of this assumption is particularly welcome in the Region IV, which together with the Region III, represents the area of transition between the aridity of the northern regions and the Mediterranean climate of the southern regions.

An antagonistic situation could be interpreted in the Regions VI and VII. These regions have low degrees of desertification and their Mediterranean climatic conditions are more favorable. Even increasing the investments to a lesser extent than for the other regions of the north, the result of the projection suggests a decrease in desertification.

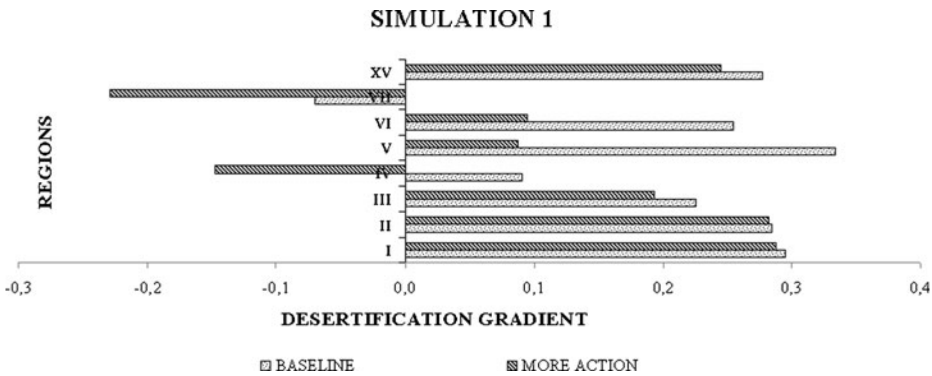

Fig. 3 Projected simulation showing the baseline situation and a scenario of increased action by the promotion agencies in the studied regions

Acording to Maestre et al. (2006), drylands are areas of the globe where the Index of Aridity (IA)—defined as the ratio of mean annual Precipitation (P) to mean annual Potential Evapotranspiration (PET)—is less than 0.65. This definition excludes hyper-arid areas of the globe where IA<0.05, such as the Atacama Desert. In the data of the Chilean map of desertification carried out by CONAF (1999), most of the land of the Regions XV, I, II and a portion of the Region III, which are in the Atacama desert, are considered areas with severe desertification condition. The Atacama Desert is hyperarid but in its Chilean area, it is crossed by several rivers fed by the melting snow of the Andes such as the rivers Lluta, San José, Loa, Copiapo, Huasco and Salado, which make its valleys suitable for agriculture and livestock since ancient times. This fact makes this part of the desert unique, and gives it an extra portion of complexity to the analysis.

Water supplies stored in glaciers and snow cover are projected to decline in the course of the century, thus reducing water availability during warm and dry periods in regions supplied by melt water from major mountain ranges (IPCC 2008). Furthermore, the water resources of the river basins in the area of study are overexploited and their lands are degraded and endangered by desertification (CONAF 1999; Cepeda and Cortes 2004; Cepeda and Novoa 2006). The area of the river basins is where the agriculture, livestock and forestry promotion agencies make their efforts in combating land degradation. The basins areas are relatively small in relation to the area considered as severely affected by desertification by CONAF (1999), which includes desert lands. We believe that for this reason the mitigation efforts carried out by CONAF, SAG and CNR are not adequately reflected in the projected simulation. In this regard, it would be desirable to incorporate the differentiation between desert and desertified lands in subsequent maps of desertification to properly assess the land degradation processes and the effectiveness of the mitigation and adaptation strategies.

The second simulation shows a scenario where the assumption has been no intervention by the ALF promotion agencies, i.e. an inaction scenario. We have given the ALF promotion agencies indicators a variation of 0% and we have maintained the rest of the indicators in the levels of the previous action projection (Table 5 and Fig. 4).

The simulation result of inaction by the ALF promotion agencies suggests that there would be an increase in desertification, even in Regions VI and VII, where climatic conditions are more favorable. This result suggests the importance of the mitigation efforts to combat desertification. In relative terms, Region VII, despite having more favorable climatic conditions, is where the increase of desertification gets mayor values. This fact indicates the great

Table 5 Percentage of variation applied to the baseline situation used in the projected simulation of inaction by the promotion agencies

Region	CNR investments (%)	SAG investments (%)	CONAF investments (%)	Farms (%)	Total population (%)	Water reservoir capacity (%)	Overgrazing (%)
I	0	0	0	20	1,10	25	−50
II	0	0	0	20	1,10	25	−50
III	0	0	0	20	1,10	25	−50
IV	0	0	0	20	1,10	50	−50
V	0	0	0	20	1,10	25	−50
VI	0	0	0	20	1,10	25	−50
VII	0	0	0	20	1,10	25	−50
XV	0	0	0	20	1,10	25	−50

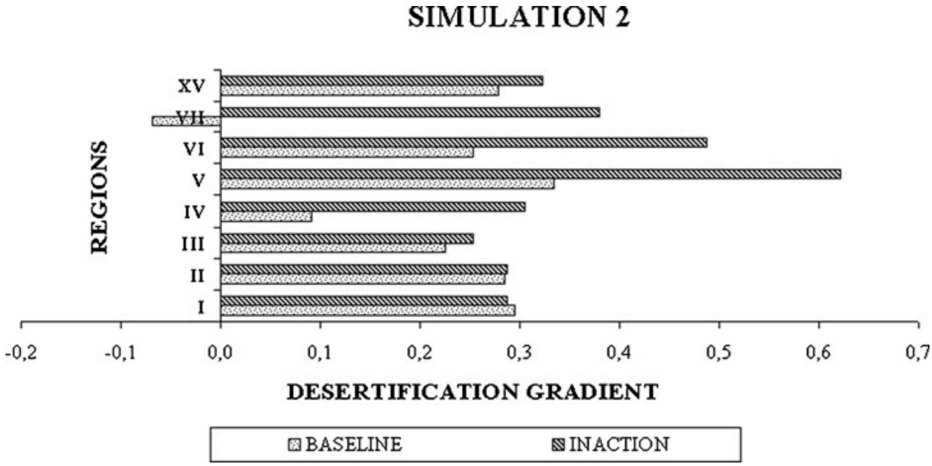

Fig. 4 Projected simulation showing the baseline situation and a scenario of inaction by the promotion agencies in the studied regions

importance of the development agencies in the fight against desertification and drought. In this inaction scenario, Regions IV and V face their worst desertification situation.

The predominant indicator pointing out to an increase in desertification is Overgrazing. About the 50% of the total number of goats in the regions under study are located in Region IV. This result is consistent, pointing out to overgrazing as a major cause of desertification in northern Chile.

Worldwide, managed grazing is the most extensive form of land use, with drylands supporting 78% of grazing on the planet (Asner et al. 2004). Grazing alters vegetation properties, water availability, soil erosion and compaction, carbon cycling, and many other ecological processes in drylands (Asner and Heidebrecht 2005). Desertification, due to overgrazing, is also documented for other areas of the world (FAO 1964; Huss 1972; Le Houérou 1981). On the other hand goat breeding is an economic activity and a source of income for the population of the Region IV, which shows a high rate of poverty (Quiroz 2007).

4 Conclusions

Given the integrative characteristics of the proposed methodology, we have been able not only to assess the mitigation strategies, but also to determine the main causes of desertification in such a complex area as the studied one, where we can find the desert itself, its desertification endangered valleys, the Andean plateau, the transitional area and the southern regions.

Our numerical model has shown the potential of integrative models not only to assess the driving forces of desertification but also to assess the forces that help mitigate desertification.

The findings of this paper suggest that the mitigation and land reclamation strategies made by CONAF, SAG and CNR play an important role in combating desertification and drought in Chile. In the absence of financial support, i.e. in an inaction scenario by the ALF promotion agencies, desertification would increase in all regions, even in Regions VI and VII, where climatic conditions are more favorable. This projection suggests the high relevance of the mitigation and land reclamation strategies of the ALF promotion agencies in combating desertification and land degradation.

During the development of our work, one of the biggest difficulties we have faced has been the collection of the data, which were widely dispersed in different Institutions depending on the characteristics of each indicator. In this regard, and for systematic assessments of the land degradation processes and subsequent evaluations of the effectiveness of the mitigation and adaptation strategies, it would be desirable to incorporate the creation of specific databases into the discussion context of the desertification.

In the areas affected by desertification and drought, it is common that the ecosystems do not have enough funding for water management and irrigation. This situation leads to an inadequate assessment of the environmental goods and services in arid zones. As a result we get a misuse of these drylands. Therefore, it is very important the promotion of innovative schemes of economic production with environmental and social sound basis in order to have a sustainable development in drylands.

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