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Corresponding Author: Dr. Javier Ibañez,

Corresponding Author's Institution:

First Author: Javier Ibañez

Order of Authors: Javier Ibañez; Jaime Martinez Valderrama; Vasilios P Papanastasis; Christakis Evangelou; Juan Puigdefabregas

Abstract: This paper refers to degradation of Mediterranean rangelands and the way it can be assessed. Firstly, a multidisciplinary, non-spatial, annual dynamic model is presented. It tries to formalize the relationships linking the dynamics of shrubs, herbs, soil, livestock and farmers' behaviour with exogenous time-scenarios regarding possible drivers of degradation, namely weather, prices and political instruments. In its simplest expression, the model does not portray a pasture-livestock system, as usually, but a shrubs-soil one. Secondly, a procedure to assess rangelands' risks of degradation is proposed. It consists in analyzing a great number of the model's annual equilibria, which are obtained by generating random-normal values for the exogenous variables of the model. Thirdly, both the model and the assessment procedure are applied to a rangeland in Lagadas County (Northern Greece). A low risk of degradation by shrub invasion and a negligible risk of degradation by erosion are found. Finally, a sensitivity analysis of parameters is carried out. It shows that some abiotic factors, especially average rainfall, would be those whose eventual change in the future could most likely make degradation risks to increase in Lagadas. Economic factors related to livestock numbers—i.e. prices and subsidies—and other factors linked to biomass consumption per animal show significant effects on controlling shrub expansion but provoking negligible impacts on erosion rates.

ASSESSING DEGRADATION IN MEDITERRANEAN RANGELANDS WITH A MULTIDISCIPLINARY DYNAMIC MODEL

Authors:

JAVIER IBÁÑEZ[a], JAIME MARTÍNEZ VALDERRAMA[b], VASILIOS P. PAPANASTASIS[c], CHRISTAKIS EVANGELOU[c], JUAN PUIGDEFÁBREGAS[b]

[a] Dpto. Estadística y Métodos de Gestión en Agricultura, Universidad Politécnica de Madrid, Spain

[b] Estación Experimental de Zonas Áridas, Consejo Superior de Investigaciones Científicas, Spain

[c] Laboratory of Rangeland Ecology, Aristotle University of Thessaloniki, Greece

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ABSTRACT

This paper refers to degradation of Mediterranean rangelands and the way it can be assessed. Firstly, a multidisciplinary, non-spatial, annual dynamic model is presented. It tries to formalize the relationships linking the dynamics of shrubs, herbs, soil, livestock and farmers' behaviour with exogenous time-scenarios regarding possible drivers of degradation, namely weather, prices and political instruments. In its simplest expression, the model does not portray a pasture-livestock system, as usually, but a shrubs-soil one. Secondly, a procedure to assess rangelands' risks of degradation is proposed. It consists in analyzing a great number of the model's annual equilibria, which are obtained by generating random-normal values for the exogenous variables of the model. Thirdly, both the model and the assessment procedure are applied to a rangeland in Lagadas County (Northern Greece). A low risk of degradation by shrub invasion and a negligible risk of degradation by erosion are found. Finally, a sensitivity analysis of parameters is carried out. It shows that some abiotic factors, especially average rainfall, would be those whose eventual change in the future could most likely make degradation risks to increase in Lagadas. Economic factors related to livestock numbers—i.e. prices and subsidies—and other factors linked to biomass consumption per animal show significant effects on controlling shrub expansion but provoking negligible impacts on erosion rates.

1.- INTRODUCTION

Mediterranean rangelands are important natural resources with an area amounting to 48% of the whole Mediterranean zone (Le Houerou 1981). They are composed of several vegetation types including grasslands, shrublands and forests. Of those types, grasslands have a limited area which is no more than 20% of the total rangelands (Papanastasis and Mansat, 1996). On the contrary, shrublands and forests cover large areas with crown densities varying from very open, where herbaceous vegetation dominates, to very dense, where herbaceous plants are almost absent. Although Mediterranean rangelands are multiple use areas, they are mainly exploited by domestic animals, especially sheep and goats.

Two processes of degradation are pointed out as possibly affecting Mediterranean rangelands: overgrazing and undergrazing. The former may be defined as the progressive reduction of rangeland's productive capacity caused by livestock overexploiting primary production. Factors cited as favouring overgrazing are: i) the communal tenure system, where farmers usually seek only short-term benefits with the consequence of overexploiting the available resources, a case named 'tragedy of commons' by Hardin (1968); ii) the maintenance of artificially high livestock numbers by supplementing both food (e.g. Wilson and Macleod, 1991) and water (e.g. Röder et al., 2007) and through the improvement of animals health status (e.g. Oesterheld et al., 1992); and iii) the subsidies that farmers receive, which might be spent in buying supplemental feed to increase the size of flocks (e.g. Papanastasis, 1993; Mendizábal and Puigdefábregas, 2003).

All these factors could be drivers of overgrazing. But for the shortages in the primary, and thus the secondary, production to definitely occur, some physical process or processes must be triggered within the rangeland. As such, erosion is the most widely reported. Its common pattern for degradation is straightforward: the reduced vegetation cover in grazed sites favours runoff and the loss of soil through erosion. This implies reductions of both the water storage capacity and the stocks of seeds and nutrients, thus restricting plants growth. Another cited process that would lead to rangeland degradation consists of a negative feedback among herb cover and infiltration (Walker et al., 1981; Rietkerk and van de Koppel, 1997). The longer exposure of soil due to grazing would result in sealing of surface pores and thus reduction of infiltration. In this way, available soil moisture decays and plant cover is further reduced. However, one point in this pattern seems uncertain: since livestock reduces biomass, the amount of water this biomass requires is lesser as well; hence, the available soil moisture could not become insufficient even if infiltration decreases.

A controversy exists on whether Mediterranean rangelands are actually affected by overgrazing or not (e.g. Le Houerou, 1981 vs. Perevolotsky and Seligman, 1998). This debate is coupled with the well-known equilibrium (e.g. Illius and O’Connor, 1999) vs. non-equilibrium (e.g. Ellis and Swift, 1988; Sullivan and Rohde, 2002) theories, although the latter is mainly focused on African rangelands. In a few words, the debate is summarized by the following question: is permanent degradation in rangelands mainly driven by abiotic factors—i.e. climate—or by management—i.e. livestock husbandry and thus human activity?

Those who doubt that Mediterranean rangelands are threatened by overgrazing claim that, in spite of they have been grazed over thousands of years, ‘there is little evidence of overgrazing /…/, except on isolated sites’ (Perevolotsky and Seligman, 1998, p.1009). It is also argued that ‘denuded or eroded land rarely becomes desert’ (Grove and Rackham, 2001, p.268) or that heavy grazing has a tenuous connection with erosion (Perevolotsky and Seligman, 1998; Rowntree et al., 2004). In fact, some studies show that erosion rates in northern Mediterranean rangelands are not critical (Kosmas, et al., 1997; Papanastasis and Kyriakakis, 2003) so that the time for these ecosystems to collapse, if any, might escape the management scale.

Undergrazing is the other process of degradation pointed out as threatening Mediterranean rangelands (Perevolotsky and Seligman, 1998; Le Houerou, 1993). It is characterized by woody biomass accumulation meaning both a lower grazing capacity and a higher fire risk. Erosion processes in bare intershrub patches have also been reported in shrub dominated rangelands (Schlesinger et al., 1990; Abrahams et al., 1999). Grazing would be the only practical way to avoid the 'green deserts' which undergrazing leads to (Perevolotsky and Seligman, 1998).

Whatever the case might be the goal of assessing degradation in rangelands, and the subsequent task of designing the tools to do it, seem to be justified. Several indicators have been proposed for that to date (Soyza et al., 1998; Sharma, 1998; Verón et al., 2006; Kéfi et al., 2007). However, most of them are based on field-measured information that only shows a present picture of a dynamic process.

This paper tries to contribute to this line of research. From our point of view, since degradation affects rangelands holistically, any procedure trying to evaluate whether it is happening or not should take into account the network of casual relationships existing among, at least, the main rangeland's constituents. Since any process of degradation is extended throughout a long period of time as well, the procedure must be able to somehow foresee the long-term effects. Both conditions seem to make the use of a kind of dynamic model almost unavoidable.

Here, the assessment of degradation risks is based on evaluating the position of many different—annual, as we will see—equilibria of a multidisciplinary dynamic model. This ultimately estimates the rates of change of total shrub biomass and soil, though it also includes equations for many other important variables: herb biomass, stocking rate, supplemental feed, etc. In short, the model formalizes a framework of causal relationships linking pasture, livestock, soil and farmers' behaviour with exogenous time-scenarios regarding possible drivers of degradation: weather, prices and political instruments. It is an extended version of the General Desertification Model presented by Ibañez et al. (2008).

The model seeks to be objective, and thus neutral to any debate, although it is quite difficult not to include any controversial particular details. Of course the model can not avoid making simplifications either. Anyway, the reader should bear in mind that the model's goal is not to quantitatively predict plausible long-term events but to be an instrument allowing warning of degradation risks at the present time, in order to identify whether a particular rangeland currently requires special attention and why.

A particular calibration of the model and an applied assessment of degradation and its most possible causes are also described in this paper. They are implemented for a common rangeland in the region of Lagadas, in northern Greece.

The dynamic model is described with detail in section 2. An analysis of its dynamic characteristics is carried out in section 3; such characteristics allow figuring out the procedure to assess degradation proposed here. The calibration of the model in a particular site within Lagadas is described in section 4. Section 5 is devoted to assess degradation risks and how different factors are sorted regarding their impacts in the studied rangeland.

2.- A THEORETICAL MODEL OF A MEDITERRANEAN RANGELAND

The model described below represents an unspecified rangeland grazed by sheep or/and goats in an EU's Mediterranean country. This rangeland consists of evergreen shrubs of various density among which herbaceous species grow. Specific parameterisation is needed for an application to a concrete site. As a normalization rule, the model is spatially referred to one hectare. Also, it has an annual basis and the equations refer to the end of the dry season (summer). Neither the spatial nor the time bases of the model—i.e. the hectare and the year, respectively—are recalled every time a variable is defined so that they must be born in mind by the reader.

Throughout the description, normal capital letters are employed to name endogenous variables, italic capital letters to denote exogenous variables and small letters to denote parameters. As it is well known, an exogenous variable has no equation in the model: the different values it takes through time can be either assigned by the user, thus forming the scenarios of simulation, or generated by sampling from a suitable stochastic process. A parameter is any exogenous variable whose values are considered not to vary with time at all.

Shrubs

The annual rate of variation of the total aboveground shrub biomass, measured at the end of the dry season, is given by the following equations:

$$\mathrm{dTSB/dt = ASP - SDR - SCR} \qquad [1]$$

$$\mathrm{ASP = PSP\ SPS} \qquad [2]$$

$$\mathrm{PSP = max\ \{0, XSP - spt\ TSB\}} \qquad [3]$$

$$\mathrm{XSP = max\ \{0, sxs\ SSM - xsi\}} \qquad [4]$$

$$\mathrm{SSM = mrr\ smoothi}\ \{\mathit{RNF}, \mathrm{rnf_t}, \mathrm{rnf_i}\} \qquad [5]$$

$$\mathrm{SPS = 1 - exp\ \{- (SOI - ss1)/ss2\}} \qquad [6]$$

$$\mathrm{SDR = fsd\ TSB} \qquad [7]$$

The equations for SCR and SOI are given in following sections.

Endogenous variables

TSB = Total aboveground shrub biomass; **ASP** = Aboveground shrub production; **SDR** = Shrub biomass death rate; **SCR** = Shrub biomass consumption rate; **PSP** = Potential aboveground shrub production; **SPS** = Soil productivity factor for shrubs; **XSP** = Maximum potential aboveground shrub production; **SSM** = Subsoil moisture; **SOI** = Soil depth

Exogenous variables

RNF = Rainfall

Parameters

s**pt** = Slope of the linear equation of the potential aboveground shrub production PSP and TSB; **sxs** = Slope of the linear equation of the maximum potential aboveground shrub production XSP and SSM; **xsi** = Maximum potential aboveground shrub production-intercept; **mrr** = Moisture-rainfall relation parameter; $\mathbf{rnf_t}$ **=** Rainfall, adjustment time for smoothing; $\mathbf{rnf_i}$ = Rainfall, initial value for smoothing; **ss1** = Shrub-soil relation parameter 1; **ss2** = Shrub-soil relation parameter 2; **fsd** = Fractional shrub biomass death rate

The annual rate of variation of the aboveground total shrub biomass is given by the balance between the aboveground production or new browse, ASP, the annual death rate, SDR, and the biomass yearly consumed by the animals, SCR (eq. 1). ASP is obtained by multiplying the potential aboveground shrub production, PSP, times the multiplier SPS which captures losses of shrub productivity linked to the loss of soil (eq. 2).

The potential aboveground shrub productivity, PSP, decreases as total shrub biomass grows in the modelled hectare, due to competition (eq. 3). The maximum potential aboveground shrub production, XSP, is linearly linked to subsoil moisture, SSM, using a negative y-intercept to reflect that no productivity is possible below some minimum amount of moisture (eq. 4). Sullivan and Rohde (2002, p.1597) cite twelve references supporting a linear relationship of this type.

SSM is linearly related to an exponential smooth of annual rainfall, *RNF* (eq. 5). This is the way the model reflects the higher inertial behaviour of the former regarding the latter. As it is well-known, an exponential smooth can be expressed as a weighted average of present and past values of the variable being smoothed, where the weights decrease exponentially as we go back over time[1]. In this way, subsoil moisture depends on present and past annual rainfall within the model, and thus it will not be cancelled out unless a number of years with no rainfall are repeated.

The model considers erosion as the process which can potentially limit primary production. To formalize this, the SPS multiplier ($0 \leq SPS \leq 1$) is used. By giving it a suitable shape, it is possible to represent the way reductions of shrubs' annual production are linked to soil losses. Here, an inverted exponential functional form has been chosen (eq. 6 and fig. 1).

FIGURE 1

In this way, the annual aboveground shrub production, ASP, will only reach its potential value, PSP, if there is sufficient soil depth in the hectare—i.e. if SPS = 1 (see eq. 2). Note that a negative value of the parameter ss1 implies that some shrub biomass exists even when the soil has been entirely removed and the bedrock has been exposed—i.e. when SOI = 0 (see fig. 1). This is observed in some species of shrubs (Grove and Rackham, 2001) whose roots get into cracks and ensure nutrients and water from deeper layers.

Finally, the shrub biomass death rate, SDR, is assumed to be proportional to the existing stock of biomass, TSB (eq. 7).

Herbs

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[1] Specifically, sx_t = smoothi(x, d, x_o) = (1/d) x_t + [1 – (1/d)] sx_{t-1} = (1/d) x_t + (1/d) [1 – (1/d)] x_{t-1} + (1/d) $[1 – (1/d)]^2$ x_{t-2} + (1/d) $[1 – (1/d)]^3$ x_{t-3} + …; d is the adjustment time: small values of d imply weights decreasing quickly—i.e. the smoothed value of x, sx, is mainly based on the most recently observed values—and *vice versa*; x_o is the initial value of sx.

The modelled pasture is also composed of herbaceous species. It is assumed that both annual and perennial herbs get dry at the end of the growing season—end of spring—to start back again their growth in the next season—autumn—from seeds or roots. Since only the aboveground biomass is represented, no state or stock variable is needed in this section of the model.

GHB = AHP – HCR [8]

AHP = PHP SPH max {0, 1 – scc TSB} [9]

SPH = 1 – exp {– max {0, SOI – msh}/hsr} [10]

PHP = max {0, phs *RNF* – phi} [11]

The equations for HCR and SOI are given in following sections.

Endogenous variables
GHB = Ungrazed aboveground herb biomass; **AHP** = Aboveground herb production; **HCR** = Herb biomass consumption rate; **PHP** = Potential herb production; **TSB** = Total aboveground shrub biomass; **SPH** = Soil productivity factor for herbs; **SOI** = Soil depth

Exogenous variables
RNF = Rainfall

Parameters
scc = Shrub biomass to cover percentage conversion coefficient; **msh** = Minimum soil depth for herb production; **hsr** = Herb-soil relation parameter; **phs** = Slope of the linear equation in the potential herb production and *RNF*; **phi** = Potential herb production-intercept

The ungrazed aboveground herb biomass at the end of any year's dry season, GHB, equals the aboveground herb production, AHP, less the biomass consumed by livestock, HCR (eq. 8). AHP is obtained by multiplying the potential annual herb production per hectare, PHP, times two multipliers (eq. 9). One of them—the max function—is the percentage of the modelled hectare not covered by shrubs, the only area where herbs can grow. Note that, regarding this first multiplier, herb biomass will completely disappear whenever:

$TSB \geq 1/scc$ [12]

The other multiplier affecting the potential annual herb production is SPH, which relates herb productivity to reductions of the soil depth, SOI (eq. 10). Again, the inverted exponential functional form has been chosen for this multiplier. A positive value of the parameter msh is expected here, meaning that herbs can not grow in the deepest soil layers (fig. 1). In other words, it is not necessary the erosion to remove the soil entirely to cancel out herb productivity. This will occur whenever:

$SOI \leq msh$ [13]

It is assumed that the modelled hectare does not correspond to a place where livestock is crowded—e.g. around watering points. Herb productivity in those special places could be drastically reduced, or entirely lost, not only by losing the soil but also as a consequence of trampling.

Summarizing, equation 9 states that for herbs to reach their potential annual production, PHP, it is necessary the absence of shrubs in the modelled hectare—i.e. TSB = 0—and also that soil is deep enough—i.e. SPE = 1. Finally, PHP is linearly related to annual rainfall, *RNF*, again using a negative y-intercept (eq. 11).

Soil

As a matter of simplifying the terminology, soil in the model refers to the entire amount of various organic and inorganic materials covering the bedrock, litter included. This is because what is sought by this model's section is to represent the annual mass balance over the bedrock, that is, the rates of materials yearly accumulated and removed, whatever their nature could be. Thus, any physical or chemical transformation happening within the soil is ignored as long as it does not imply significant mass variations.

$$dSOI/dt = BWR + OMR - SER \quad [14]$$

$$BWR = \max\{0, pwr - wsr\ SOI\} \quad [15]$$

$$OMR = (GHB + SDR + oma\ SKR)\ (1 - fod)\ mdc \quad [16]$$

$$SER = BSE\ [\max\{0, 1 - scc\ TSB\}\ \exp\{-ehr\ GHB\} + \min\{1, scc\ TSB\}\ \exp\{-esr\ TSB\}] \quad [17]$$

The equation for SKR is given in a following section.

Endogenous variables
SOI = Soil depth; **BWR** = Bedrock weathering rate; **OMR** = Organic matter deposition rate; **SER** = Soil erosion net-rate; **GHB** = Ungrazed above ground herb biomass; **SDR** = Shrub biomass death rate; **SKR** = Stocking rate; **TSB** = Total aboveground shrub biomass

Exogenous variables
BSE = Bare soil erosion rate

Parameters
pwr = Potential bedrock weathering rate; **wsr** = Weathering-soil depth relation parameter; **oma** = Organic matter per animal; **fod** = Fractional organic matter decomposition rate; **mdc** = Mass to depth unit conversion coefficient for organic matter; **scc** = Shrub biomass to cover percentage conversion coefficient; **ehr** = Erosion-herb biomass relation parameter; **esr** = Erosion-shrub biomass relation parameter

The stock of soil grows annually due to the bedrock weathering rate, BWR, and to the net-rate of deposited organic matter, OMR (eq. 14). The former decreases as soil depth increases because the bedrock surface is less affected by weather (eq. 15). The organic matter comes from herbs' and shrubs' dead materials and from livestock manure. Since herbs get dry at the end of the growing season, all their ungrazed biomass, GHB, is added to the soil each year. A fraction, fod, of the yearly deposited organic matter is released to the atmosphere as CO_2 in the decomposition process (eq. 16)

Losses of soil are due to positive net-rates of erosion, that is to unbalances between the inner erosion rates in the modelled hectare and the deposition of soil coming from upslope areas (eq. 14). Such annual net-rate of erosion, SER, has to be related to both the ungrazed herb biomass, GHB, and the total shrub biomass, TSB—both measured at the end of the dry season—since these are the only variables referred to vegetation within the model. However, this seems reasonable since vegetation cover is minimal at the onset of the rainy season so that the greatest erosion rates of the year happen in such a period. The relationship is formalized as a weighted average of the erosion rates in the herb and shrub shares of the hectare, where the weights are the respective cover percentages (recall eq. 9). Conventional negative exponential functional forms (e.g. Elwell and Stocking, 1976) are used to formulate both erosion rates (eq. 17).

On the one hand, the bare soil erosion rate, *BSE*—i.e. the erosion rate when TSB = GHB = 0—depends on the characteristics of the soil and the slope of the modelled hectare, yet these two factors can be taken as fixed for a given hectare. On the other, *BSE* also depends on the intensity and timing of rainfall, what makes such an exogenous variable to follow stochastic patterns in the course of years. These patterns may be assumed independent of the amounts fell. Indeed, a high amount of rainfall can provoke little erosion if its intensity is low and it occurs when the soil is more covered. Conversely, large losses of soil can be triggered in an overall dry year if events of rainfall, though scarce, are intense enough and happen when the soil is more exposed.

Stocking rate

The stocking rate in the modelled hectare is determined by means of the following equations:

$$\text{SKR} = \max\{\text{GMA}^{e}/\text{gm1}, (1 - \text{dps})\,\text{rgh}\} \qquad [18]$$

$$GMA^{e} = \text{smoothi}\ \{GMA, gma_{t}, gma_{i}\} \qquad [19]$$

$$GMA = \mathit{PRM}\ MYA + (sbh/SKR) + ika - \mathit{PRS}\ SFA - oca \qquad [20]$$

$$MYA = pmy\ (1 - \exp\{- mer\ IEA\}) \qquad [21]$$

The equations for IEA and SFA are given in following sections.

Endogenous variables
SKR = Stocking rate; **GMA**$^{\mathbf{e}}$ = Estimated gross margin per animal; **GMA** = Gross margin per animal; **MYA** = Milk yield per animal; **SFA** = Supplemental feed consumed per animal

Exogenous variables
PRM = Price of milk; ***PRS*** = Price of supplemental feed

Parameters
gm1 = Gross margin per animal that makes SKR to be one; **dps** = Decoupling percentage of payments; **rgh** = Subsidized animals (rights) in the hectare; $\mathbf{gma_t}$ **=** Gross margin per animal, adjustment time for smoothing; $\mathbf{gma_i}$ **=** Gross margin per animal, initial value for smoothing; **sbh** = Total subsidies to the hectare; **ika** = Income from the selling of kids per animal; **oca** = Other cost per animal (not supplemental feed); **pmy** = Potential milk yield per animal; **mer** = Milk-energy intake relation parameter

The central assumption of this model's section is that the stocking rate, SKR, depends on the expected profitability of the grazing business. If profitability maintains high during enough time, either the number of farmers or the size of the flocks, or both, will grow within the region resulting in the increase of the average stocking, and *vice versa*. Thus, a linear relationship between SKR and the expected gross margin per animal, GMA^{e}, is hypothesized (eq. 18). The proportionality parameter, gm1, is expressed as divisor to make it positively related to the average opportunity cost of farmers. In this way, the better the average alternative rent outside livestock production—i.e. the greater gm1—the lesser the number of farmers staying in the business, and thus the average stocking rate.

Equation 18 includes a max function to account for the constraints that the policy instruments being in force in the European countries establish on SKR. The CAP currently subsidize sheep/goat farmers with a Single Farm Payment, decoupled from production and animal numbers, which could be half combined with a system of flat premiums per "right"—i.e. per eligible sheep/goat—plus supplementary premiums if certain requirements are fulfilled. Each Member State has decided whether to follow the partially or the entirely decoupled system (http://ec.europa.eu), and this can be reflected in the model by means of the decoupling percentage parameter, dps. With the max function of equation 18 the modelled stocking rate will exceed the number of rights per hectare if the expected gross margin per animal, GMA^e, is high enough, in spite the fact some animals will not receive subsidies. This will be the common situation when the decoupling percentage, dps, is either 0.5 or 1. Nevertheless, since subsidies are incomes with no risk, so that they are always worth to be ensured, it is assumed that the stocking rate will never fall under the number of rights per hectare, whatever profitability could be.

Farmers' expectation about gross margin per animal, GMA^e, is obtained by exponential smoothing (eq. 19). Hence, GMA^e is a weighted average of past observed values of the actual gross margin per animal, GMA, where the weights decrease exponentially as we go back over time (recall footnote 1). This is a conventional way to represent the forming of expectations about uncertain variables, so-called adaptable expectations. Note that by assuming a farmers' response based on averaging past observed values the impact of any shift in GMA on the stocking rate will be distributed, or delayed, along several years. As other kind of lags (Walker, 1993), this one could also influence rangeland dynamics.

Indeed, if farmers would not lag their responses and thus they stock yearly on the basis of the current gross margin per animal—i.e. if GMA^e = GMA—the average stocking rate, SKR, will change with any annual variation of profitability. Moreover, the entire impact of each change on GMA, for example due to biomass shortage or a punctual variation of prices, would be reflected immediately on SKR[2]. This kind of farmers' behaviour, which Anderies et al. (2002) call 'perfectly reactive strategy', could have the desirable consequence of making the stocking rate, and thus the pressure on biomass, to be reduced in dry years. However, this will only be entirely true as long as prices and subsidies do not take especially advantageous values in the same years. Yet this perfectly reactive strategy can hardly be expected in Mediterranean rangelands.

More realistically, the forming of expectations about the gross margin per head implies averaging a number of past observed values—i.e. a positive value of gma_t—and thus an inertial or delayed farmers' response. In this way, any shift of GMA in an isolated year, either upward or downward, will only be reflected partially on GMA^e. The greater the number of averaged years the lesser the shift that any single year's profitability will provoke on farmers' expectations. Therefore, if the stocking decisions delay long, the modelled hectare will be neither de-stocked nor re-stocked significantly from year to year and the eventual advantages of the perfectly reactive strategy will be lost.

The equation for the gross margin per animal, GMA (eq. 20), considers the incomes coming from the selling of milk and kids and the subsidies perceived per head. Farmers would be price takers, or in other words, the prices of milk, *PRM*, and supplemental feed, *PRS*, would be determined by markets and not influenced by the production and demand happening in the region. Hence both *PRM* and *PRS* are considered exogenous variables thus allowing scenarios either assigned by the user or generated stochastically. Total subsidies to the hectare, sbh**,** incomes from the selling of kids, ika, and other costs per animal different from supplemental feed, oca, are all simplified as parameters.

The milk yield per animal, MYA, is related to the individual intake of energy, IEA, by means of an inverted exponential functional form (eq. 21 and fig. 1). Thus, the milk

[2] The existence of rights could constrain reductions of the livestock numbers.

yield per head grows with the intake of energy until a potential or saturation value, pmy, is reached. The values of both pmy and the shape-parameter mer depend on the breed being considered.

Consumption of biomass

The following is the set of equations used to determine the rates of herb and shrub biomasses yearly consumed in the modelled hectare.

$$RBA = pbi - bss\ SFA^{t} \quad [22]$$

$$ABP = peh\ AHP + pen\ ASP \quad [23]$$

$$NBA = \min\{RBA, ABP/SKR\} \quad [24]$$

$$HCR = HBA\ SKR \quad [25]$$

$$HBA = HPA\ NBA \quad [26]$$

$$HPA = (peh\ AHP/ABP)^{hpr} \quad [27]$$

$$SCR = \min\{(NSA + OSA)\ SKR, pes\ TSB\} \quad [28]$$

$$NSA = (1 - HPA)\ NBA \quad [29]$$

$$OSA = RBA - NBA \quad [30]$$

The equation for SFA^{t} is given in the following section.

Endogenous variables
RBA = Biomass normally required per animal; **SFA**$^{\mathbf{t}}$ = Target supplemental feed consumed per animal; **ABP** = Available aboveground biomass production; **AHP** = Aboveground herb production; **ASP** = Aboveground shrub production; **NBA** = New biomass consumed per animal; **SKR** = Stocking rate; **HCR** = Herb biomass consumption rate; **HBA** = Herb biomass consumed per animal; **HPA** = Herb proportion in new biomass consumed per animal; **SCR** = Shrub biomass consumption rate; **NSA** = Shrub new biomass consumed per animal; **OSA** = Shrub old biomass consumed per animal; **TSB** = Total aboveground shrub biomass

Parameters
pbi = Biomass intake per animal without supplemental feed; **bss** = Biomass-supplement substitution coefficient; **peh** = Proportion of eatable herb production; **pen** = Proportion of eatable shrub production; **hpr** = Consumed-available herb proportions relation parameter; **pes** = Proportion of eatable total shrub biomass

The amount of biomass normally required by one animal, RBA, equals the potential biomass intake per head, which is assumed to be a parameter, named pbi, less a fraction, bss, of the target amount of supplemental feed supplied per animal, SFA^t (eq. 22). Therefore, the model allows considering different biomass-supplement substitution ratios by giving non-zero values to bss.

The availability of new biomass, ABP—i.e. that produced in the current year—is the sum of the eatable fractions of the herb and shrub aboveground production (eq. 23). Since the animals prefer this new biomass, the amount yearly consumed per head, NBA, will equate the required amount of biomass, RBA, unless ABP is not sufficient in the modelled hectare (eq. 24). The model considers that the eatable fraction of the current year's biomass productions, peh for herbs and pen for shrubs, remain fixed with time. This simplification requires assuming that unpalatable species are negligible.

The total herb biomass yearly removed by livestock in the modelled hectare, HCR, is simply the herb biomass consumed per animal, HBA, times the stocking rate, SKR (eq. 25). HBA is a fraction, named HPA, of the amount of new biomass consumed per head, NBA (eq. 26). It is assumed that the greater the relative availability of any type of biomass within the hectare, herbs or shrubs, the higher is the pressure of livestock on it. This means that, although not explicitly shown by the equations, the ratio of grazers/browsers—i.e. sheep/goats—within the stocking rate, SKR, would differ from year to year. This reflects the fact that shepherds decide where to lead what animals by looking at pasture's composition. Therefore, the average fraction of herbs, HPA, in the amount of new biomass consumed per animal is related to the proportion of eatable herb biomass within the hectare's available new biomass (eq. 27); the parameter hpr allows managing the shape of this relationship.

The total shrub biomass yearly removed by livestock, SCR, will be the amount of shrub biomass consumed per animal times the stocking rate, SKR, unless SCR overcomes the eatable fraction of the total shrub biomass, TSB (eq. 28). The amount of shrub biomass consumed per head could be made up of shares of new and old biomasses, NSA and OSA, respectively. The former is simply the remainder fraction, 1 – HPA, of the total new biomass consumed per head, NBA (eq. 29). As indicated before, this fraction is positively related to the availability of new shrub biomass within the hectare. The old shrub biomass consumed per head, OSA, is assumed to be the difference between the normally required and the actual new biomass consumed per animal (eq. 30). In this way, the old shrub materials will only be consumed in years of scarcity where NBA < RBA.

Supplemental feed

Farmers use supplemental feed to make the animals reaching the targeted energy intakes. Livestock have also water at their disposal at any time, droughts included. The following are the equations determining the amount of supplemental feed and the energy intake per animal.

$$\mathrm{SFA} = \mathrm{SFA}^{t} + \mathrm{SFA}^{x} \quad [31]$$

$$\mathrm{SFA}^{t} = (\mathrm{IEA} - \mathrm{pbi\ BEC})/(\mathrm{sfe} - \mathrm{bss\ BEC}) \quad [32]$$

$$\mathrm{BEC} = \mathrm{hec\ HPA} + \mathrm{sec}\ (1 - \mathrm{HPA}) \text{ if } \mathrm{ABP} > 0; = 0 \text{ if } \mathrm{ABP} = 0 \quad [33]$$

$$\mathrm{IEA}^{o} = \ln \{[(\mathrm{sfe} - \mathrm{bss\ BEC})\ \mathit{PRM}\ \mathrm{pmy\ mer}]/\mathit{PRS}\}/\mathrm{mer} \quad [34]$$

$$\mathrm{IEA} = (1 + \mathrm{sbo})\ \mathrm{IEA}^{o} \quad [35]$$

$$\mathrm{SFA}^{x} = \max \{0, (\mathrm{IEA} - \mathrm{sfe\ SFA}^{t} - \mathrm{hec\ HBA} - \mathrm{sec\ NSA})/\mathrm{sfe}\} \quad [36]$$

Endogenous variables

SFA = Supplemental feed consumed per animal; **SFA^{t}** = Target supplemental feed consumed per animal; **SFA^{x}** = Extra supplemental feed consumed per animal; **IEA** = Intake of energy per animal; **BEC** = Biomass average energy content; **HPA** = Herb proportion in new biomass consumed per animal; **IEA^{o}** = Optimum intake of energy per animal; **HBA** = Herb biomass consumed per animal; **NSA** = Shrub new-biomass consumed per animal

Exogenous variables

PRM = Price of milk; ***PRS*** = Price of supplemental feed

Parameters

pbi = Biomass intake per animal without supplemental feed; **sfe** = Supplemental feed energy content; **bss** = Biomass-supplement substitution coefficient; **hec** = Herb energy content; **sec** = Shrub energy content; **pmy** = Potential milk yield per animal; **mer** = Milk-energy intake relation parameter; **sbo** = Rate of systematic bias from optimum energy intake per animal

The total amount of supplemental feed consumed per head, SFA, could be made up of a normal target share, SFA^{t}, and an occasional extra share, SFA^{x}, only supplied in years of biomass scarcity (eq. 31). SFA^{t} is the amount of supplemental feed needed to reach the target intake of energy per head, IEA, in a normal year where the animals are able to get the required biomass from the annual biomass production—i.e when NBA = RBA.

Some operations are needed to get the mathematical expression of SFA^{t} (eq. 32). Indeed, using eqs. 22, 26 and 29 and being sfe, hec and sec the per unit energy contents of supplemental feed, herb biomass and new shrub biomass, respectively, for a normal year where NBA = RBA it is verified that:

$$\mathrm{IEA} = \mathrm{sfe}\ \mathrm{SFA}^{t} + \mathrm{hec}\ \mathrm{HBA} + \mathrm{sec}\ \mathrm{NSA} =$$

$$= \mathrm{sfe}\ \mathrm{SFA}^{t} + \mathrm{hec}\ \mathrm{HPA}\ (\mathrm{pbi} - \mathrm{bss}\ \mathrm{SFA}^{t}) + \mathrm{sec}\ (1 - \mathrm{HPA})\ (\mathrm{pbi} - \mathrm{bss}\ \mathrm{SFA}^{t}) =$$

$$= \mathrm{sfe}\ \mathrm{SFA}^{t} + (\mathrm{pbi} - \mathrm{bss}\ \mathrm{SFA}^{t})\ [\mathrm{hec}\ \mathrm{HPA} + \mathrm{sec}\ (1 - \mathrm{HPA})] =$$

$$= \mathrm{sfe}\ \mathrm{SFA}^{t} + (\mathrm{pbi} - \mathrm{bss}\ \mathrm{SFA}^{t})\ \mathrm{BEC} \qquad [37]$$

Equation 32 is obtained simply by solving eq. 37 for SFA^{t}. BEC is the average unitary energy content of the new biomass consumed per animal, which is zero in a year of no biomass production (eq. 33).

Since the milk yield per animal, MYA, increases non-linearly with IEA until a saturation value (recall eq. 21) and the supplemental feed supplied per head grows linearly with IEA (eq. 32), an optimal intake of energy, IEA^o, exits which render the maximum gross margin per animal. This optimal value is obtained for a year with no biomass scarcity using the conventional first-order maximum condition: firstly substituting MYA (eq. 21) and SFA^t (eq. 32) in the expression of GMA (eq. 20), then differentiating GMA with respect to IEA and finally solving the equation dGMA/dIEA = 0 for IEA. The resulting expression is equation 34.

Note that the optimum intake of energy, IEA^o, is positively related to the price of milk, *PRM*, and the particular breed, through pmy and mer, and negatively related to the price of supplemental feed, *PRS*. Therefore, if *PRM* increases or/and *PRS* decreases in some year, it will be optimal to increase the animals' intake of energy in such a year in a definite amount given by IEA^o. It is unlikely that farmers know exactly the values taken by IEA^o through time, or in other words, that they behave in a perfect optimal way. However, overall rationality is assumed for farmers' responses to price variations so that the target intake of energy per head, IEA, keeps track of the optimum value, IEA^o. For the sake of simplicity, the bias between both energy intakes, sbo, is considered to be systematic (eq. 35).

In a year with scarcity of biomass, where NBA equals ABP/SKR and is lesser than RBA (recall eq. 24), the amount SFA^t given by eq. 32 is no longer able to make one animal to complete the targeted intake of energy, IEA[3]. Therefore, in such years each animal is supplied with the additional amount of supplemental feed, SFA^x, which serves to fill the gap until IEA (eq. 36). Another particularity of years with biomass shortage is that the intake of energy given by eq. 34 is no longer optimum[4]. However, the model neglects this subtlety which hardly could be noticed by farmers. This means that in any

[3] It can be checked that, after assuming negligible the energy content of the old shrub biomass, for one animal to intake IEA when NBA = ABP/SKR the amount of supplemental feed must be SFA^t = [IEA – (ABP/SKR) BEC]/sfe, a quantity which is always greater than eq. 32's.

[4] It can be checked that IEA^o = ln {sfe *PRM* pmy mer/*PRS*}/mer when NBA = ABP/SKR.

simulated year in which NBA < RBA the model will make the rate of deviation between the actual and the optimum intake of energy to be greater than its normal value, sbo (recall eq. 35).

3.- MODEL DYNAMICS: SUSTAINABILITY AND DEGRADATION

The theoretical model described before has two state variables, total shrub biomass, TSB, and soil depth, SOI, whose annual rates of variation are defined in equations 1 and 14, respectively. It may be checked that, by suitably substituting all the rest of endogenous and exogenous variables into these two equations, the whole model is condensed into a couple of dynamic equations of the form:

dTSB/dt = φ[present and past values of TSB, SOI and *EXOGENOUS VARIABLES*] [38]

dSOI/dt = ψ[present and past values of TSB, SOI and *EXOGENOUS VARIABLES*] [39]

Therefore, rangelands are not represented here by means of a livestock-biomass dynamic system, as normally do the so-called ‘equilibrium models’ (e.g. Noy-Meir, 1975), but by means of a shrubs-soil one. This two-dimensional system, whose complicated equations involve all of the model’s parameters, relates the dynamics of shrub biomass and soil depth within a particular rangeland—i.e. one whose parameters has been fixed—to time-scenarios of the exogenous variables—i.e. to weather (*RNF*, *BSE*) and prices (*PRM*, *PRS*). Since the rest of endogenous variables—i.e. herb biomass, stocking rate, erosion, etc.—ultimately depends on TSB, SOI and the exogenous variables, as it may be checked in the expanded model, their dynamics could be entirely recovered from those yielded by φ and ψ.

From an applied point of view, the model is able to generate time-trajectories of all the endogenous variables along a period established by the user. Three inputs are necessary for that: i) suitable values for the set of parameters—i.e. to calibrate the model; ii) a pair of initial values for TSB and SOI and iii) a detailed time-scenario for each exogenous variable.

Scenarios where the exogenous variables do not change with time

In order to understand more deeply the model dynamics it is worth considering the theoretical situation of converting the whole set of exogenous variables into parameters. This means to take every exogenous variable as fixed in time, for example, at their respective average value. In this way, once the set of parameter values are assigned, exogenous variables now included, the time-trajectories of all of the system's endogenous variables only depend on the initial values of TSB and SOI. In other words, it is possible to foresee the long-term state of the whole system just by knowing what the values of both TSB and SOI currently are.

For this task the following two equations are relevant:

$$dTSB/dt = \varphi[TSB, SOI] = 0 \qquad [40]$$

$$dSOI/dt = \psi[TSB, SOI] = 0 \qquad [41]$$

These are the nullclines of the system: the shrub-nullcline and the soil-nullcline, respectively. Their intersection points, of the type (SOI, TSB), are steady states or equilibria for the whole system. In such points, the rates of variation of both TSB and SOI cancel out so that their time-trajectories, and thus those of all the rest of endogenous variables, settle down to constant values[5]. Since φ and ψ have complicated expressions in our model, the nullclines can only be found in practice by programmed numerical procedures.

Figure 2 shows a first illustrative instance, called case A, of all the relevant dynamic elements of our model. The drawing corresponds to a particular set of values of both parameters and the exogenous variables. It shows the phase plane with axis SOI-TSB containing: i) the shrub-nullcline (dashed line); ii) the soil-nullcline (solid line with two branches); iii) the equilibrium points of the system (the black and white circles); iv) the signs or directions of the functions φ and ψ in each region delimited by the two nullclines (pairs of perpendicular solid arrows where the vertical one refers to φ and the horizontal one to ψ); and v) some examples of time-trajectories followed by the state variables (dashed arrows).

FIGURE 2

In case A, the nullclines intersect at three points[6] and thus there are three possible equilibria for the system. The equilibrium marked with a white circle is an unstable one. Only two particular time-trajectories lead to it meaning that the probability for the system to find this equilibrium is zero. However, those two trajectories define the line called separatrix which is important because it marks out the sustainable and unsustainable regions of the phase plane. Indeed, on the one hand, every time-trajectory starting at any pair of initial values (soi_i, tsb_i) located to the right of the separatrix—i.e. within figure’s white-shaded area—will reach the S-equilibrium, or in other words, will

[5] The present and the past values of TSB and SOI will coincide then; this is why eqs. 40 and 41 neglects the latter.

[6] In this instance of case A, the left-most part of the soil-nullcline coincides with the lowest part of the vertical axis. This is why point D is also an intersection point.

be attracted by S, a point where both the soil depth and the shrub biomass are relatively high. On the other, every time-trajectory starting at any point to the left of the separatrix—i.e. within the grey-shaded area—will be attracted by the D-equilibrium, which in this instance of the case A corresponds to a degraded hectare devoid of soil, and thus of herbs too, though some shrub biomass grows on bedrock's cracks[7].

Note that the D-equilibrium's region of attraction—grey-shaded—is made up of points with a low soil component. Therefore, under case A, inexorable degradation will only occur to an initially eroded system, or conversely, sustainable dynamics will go on for any normal system. Something important must also be noticed regarding the S-equilibrium. Recall that model's equations state that no herb biomass will grow in the hectare if either the total shrub biomass overcomes 1/scc (eq. 12) or the soil depth is under msh (eq. 13); both thresholds are marked in fig. 2. It can be seen that point S is bellow 1/scc and to the right of msh, meaning that the pasture at such an equilibrium is composed of both herbs and shrubs. However this is a result linked to the particular set of values assigned to parameters and endogenous variables in this instance of the case A. Some other sets of values had made either $\text{SOI} < \text{msh}$, $\text{TSB} > 1/\text{scc}$, or both, at point S, thereby representing a system which tends to be entirely dominated by shrubs in the long-term.

Figure FIGURE **3** shows a second instance of model's nullclines, called case B. Of course, it is obtained by fixing the parameters and exogenous variables at different values than those used in case A.

FIGURE 3

[7] For other instances of the case A, the left-most part of the soil-nullcline does not coincide with the vertical axis thus intersecting with the shrub-nullcline at a point where $\text{SOI} > 0$ (see, for example, the case B illustrated bellow). Of course, it is also possible that the shrub-nullcline intersects the horizontal axis, instead of the vertical one, meaning that no shrub biomass can grow on the deepest layers of soil.

Here only a D-equilibrium, with low values of both SOI and TSB, exists. Therefore, if the system's nullclines would display as some instance of the case B, every system's time-trajectory, starting anywhere, will lead to degradation[8].

If we hold the assumption of considering a particular set of fixed values not only for the parameters but also for the exogenous variables, the modelled rangeland will show a particular instance of only one of the two described types of dynamics, either A or B. In this way the model allows to assess whether a studied rangeland would be sustainable—would tend towards a S-equilibrium—or degraded—would tend towards a D-equilibrium—under theoretical invariable time-scenarios. An assessment like that does not lack of interest indeed, especially if the scenario is made up of average values.

Scenarios where only one parameter or exogenous variable change with time

It must be highlighted that it would suffice to suitably change the value of just one of the parameters or exogenous variables within the fixed set considered so far for the system to shift from one to the other overall dynamic framework.

For example, we could find that the system is under case-A dynamics after assigning average values to all of the parameters and exogenous variables, meaning that the modelled rangeland would be sustainable under invariable average conditions. However, the overall system dynamics, and the associated assessment of sustainability, could drastically change if, for instance, the value of gm1 was sufficiently decreased from some year on—i.e. if farmers' average opportunity cost shifts to a lower value and thus the average stocking rate moves to a higher one (recall eq. 18). Here, the passage to

[8] Note that the D-equilibrium could be positioned at the vertical axis, as in fig. 2, meaning that the system tends towards the entire loss of the soil in the long term.

the case-B dynamics of degradation happening after such all-other-things-being-equal change of scenario had to be undoubtedly attributed to overstocking.

Likewise, case A could also become case B if, without changing gm1, the annual rainfall would be dropped below a certain under-average value from some year on. In this case, degradation could be attributed exclusively to a change towards a drier weather—a climatic change indeed, given its constancy—but again because all other things are being unrealistically equal.

Scenarios where all the exogenous variables simultaneously change with time

The previous reasoning helps to figure out what will happen when the theoretical assumption of all the exogenous variables remaining invariable through time is given up. If such variables are allowed to change annually, either stochastically or by means of scenarios specified by the user, the position of the system's nullclines will vary from year to year so that a different equilibrium will be the system's attractor each year. It is possible then that cases A and B alternate in the course of time with different patterns.

However, it is quite important to note that the current year's position of an equilibrium point within the phase plane is not necessarily the current year's position of the actual system's time-trajectory. Rather, both positions will likely differ. The actual time-trajectory will move each year towards the current system's attractor, at least roughly. But unless the same attractor is repeated a sufficient number of years, the actual time-trajectory will be normally far from any equilibrium.

The example shown in fig. 4 tries to clarify this important issue usually missed in the literature. It corresponds to the following sequence of four imaginary years: normal (year 1), severely dry with some torrential storms (year 2), humid (year 3) and moderately dry (year 4). The figure shows the four annual equilibria or system's attractors, the four time-trajectories which would lead to every equilibrium if the exogenous variables were fixed to their current values from the corresponding year on (dashed arrows) and the actual time-trajectory (solid arrow).

FIGURE 4

A unique set of parameter values is used in this example. Then, the long-term equilibrium in the average year 1, EQ1, which is of the case A's type S, results after assigning average values to all of the exogenous variables. The long-term equilibrium corresponding to the very bad year 2, EQ2, which is of the case B's type D, results by assigning a very low value to annual rainfall, *RNF*, and simultaneously an above-average value to the bare soil erosion rate, *BSE*; the two other exogenous variables—*PRM* and *PRS*—would vary regarding year 1 too, though not significantly. Finally, above-average and bellow-average values of *RNF* are used to obtain the S-equilibria EQ3 and EQ4, respectively, while the three other exogenous variables change slightly with regard their average values.

The initial actual position of the system at the beginning of year 1 (point y.0 in fig. 4) depends on past events so that it is rather arbitrary here. At the end of year 1 (point y.1), the actual time-trajectory gets closer to its current attractor, EQ1, but without reaching it. Only if the particular scenario of year 1 were maintained constant during a number of years the system would reach EQ1. For that, it would follow the trajectory marked by the dashed arrow going from y.0 to such equilibrium. But actually, at the end of the bad year 2 (point y.2) the system losses soil with regard to the end of year 1—i.e. the actual time-trajectory shifts to the left. In this way, the system aims at EQ2 yet being far from reaching it. Again, EQ2 would only be reached after many years of repeating exactly the same scenario of year 2; for that, the system would follow the dashed arrow joining y.1 and EQ2. Likewise, the actual time-trajectory seeks the respective current equilibria in years 3 and 4 but without reaching them.

This example serves to illustrate how one and the same dynamic model is able to show both 'disequilibrium' (Illius and O'Connor, 1999, p. 800) and 'non-equilibrium' (e.g. Ellis, and Swift, 1988; Sullivan and Rohde, 2002) dynamics. The former is caused by different non-reached equilibria successively occurring in the course of time; the latter will happen when those equilibria frequently include type-D ones—i.e. equilibria corresponding to a degraded system, though equilibria after all.

Note now that the actual time-trajectory slowly shifts upward and leftward in the course of the four exemplified years. This means that the system follows an overall tendency of degradation in such years since there is progressively less soil and more shrubs in the rangeland. In fact, degradation in the modelled rangeland might be rigorously defined as the progressive displacement of the system to a leftward or/and upward direction within the phase plane.

This idea is further developed further in fig. 5. It shows the phase plane mapped into three regions: permanent degradation (grey), reversible degradation (dotted) and no degradation (white). It also shows some examples of degrading tendencies—not actual time-trajectories—for the modelled rangeland (dashed arrows).

FIGURE 5

Note that the boundaries of the white region are marked out by the thresholds 1/scc and msh of eqs. 12 and 13. Therefore, when the system is within this region, pasture will be made up of both herbs and shrubs—except for the points at the horizontal axis where only herbs exist. The white region is considered here to be that of no degradation[9]. Soil depth is under msh at any point within the grey region meaning that herbs have disappeared in the hectare and thus shrubs dominate. We know that this is because of, once SOI < msh, the upper soil's layer allowing herb growth is lost by erosion. Had the system entered into this grey region, it will be necessary for the soil to newly form the composition and structure of such a layer in order to recover herb production. This process would last for a very long time and this is why the grey region is considered as that of permanent degradation. Within the dotted region, shrubs entirely dominate the modelled hectare too, since TSB > 1/scc, yet the soil's upper layer is not lost. Therefore, it would be possible for any system positioned in such a region to recover herb production quickly, for example, with fire. This makes the dotted region to be labelled as that of reversible degradation.

Therefore, a process of degradation might be defined as an overall system's displacement from the white region to any other region. Moreover, the leftward component of such a displacement is the most undesirable one. Fig. 5 shows four examples of such degrading tendencies. Trends 1 and 2 leave the white region leftward while 3 and 4 do it upward. When the former happens degradation is mainly due to the loss of soil through erosion, although its consequence is shrub dominance, while in the latter degradation is exclusively due to shrubs invasion.

After being degraded by erosion the system could either go to the region where D-equilibria are placed (tendency 1) or turn up (tendency 2). The latter could occur, for example, if flocks were significantly reduced once the herb biomass is lost, thus allowing shrub recovering. The system could also end up in the same upper left part of the phase plane by following a pathway of shrub invasion (tendency 3). This would

[9] Those readers thinking that shrub-dominated rangelands are not necessarily degraded ones please note that the most important thing here is to describe the possible rangeland dynamics and not trying to label the phase plane's regions to achieve a unanimous agreement.

occur if the erosion rates were greater in the shrub-dominated rangeland than in the mixed one so that a leftward component grows as herbs are being lost. In turn, tendency 4 represents a system evolving towards a shrub dominated state but without net losses of soil.

Having in mind the explanation regarding the example drawn in fig. 4, it may be seen that the system will evolve towards any given region within the phase plane if the annual equilibria turn out to be positioned in such a region most frequently. For example, if the rangeland currently is within the white region but most of the annual equilibria are within the grey region, the actual time-trajectory, though wandering around its overall trend, will drift faster or slower towards a more eroded state dominated by shrubs. Instead, if the rangeland currently is within the white region and most of the annual equilibria are into the same region, the system will remain non-degraded.

As explained before, for a given rangeland—i.e. one whose parameters are fixed—the position of any annual system's equilibrium depends on the values that the exogenous variables are currently taking. It follows that, for example, if high values of *BSE* and *PRM*—i.e. torrential rainfalls and high prices of milk—and also low values of *RNF* and *PRS*—i.e. droughts and low prices of supplemental feed—predominate within a (multiyear) scenario, it will be easier the case B, and thus D-equilibria, to frequently appear, thereby favouring system's degradation through erosion. Conversely, if a scenario includes many low values of *BSE* and *PRM* and also many high values of *RNF* and *PRS* it will favour an upward tendency in the system.

There are infinite possible combinations for the values taken by our four exogenous variables within the scenarios. Moreover, the dynamics associated with any particular scenario will be conditioned by the concrete system's characterization, that is, by its particular set of parameter values. Therefore, any process of degradation will likely occur under the confluence of a number of factors. In other words, in a realistic system evolving under scenarios not constrained to the all-other-things-being-equal condition, different causes of degradation will normally be intermingled. Thus, the relative weights of climatic factors and livestock—rather profitability—on degradation will vary, in principle, from one particular site to another, and even among different periods of time for the same site. Could it be expected that some of those weights generally dominate? It might be, but we will not defend any overall position on the matter here. After all, to help measure those weights in concrete applications is one of the aims the model has been built for, so it is worth waiting for several applications to be done for us to consolidate any position. One of such applications is precisely presented for illustration in the next two sections.

Finally, as the reader would have possibly noted, our previous analysis neglects any reference to the speed of degradation processes. Yet this is all but a minor issue really. The set of annual equilibria of a given rangeland could include a large number of D-ones but it could be that the time for the system to reach the area of such points is thousands of years so that the worry about degradation is considerably mitigated if not entirely forgiven. Therefore, any assessment of a rangeland's degradation risk made with the model will be improved if an estimation of how long the process could last is additionally provided. The analysis of annual equilibria allows making an overall qualitative assessment of such a time. But for a quantitative estimation the model has to be used in a conventional, time-running, way. We will illustrate all this issues by making an application of the model to a concrete Mediterranean rangeland.

4.- THE STUDY CASE OF LAGADAS (GREECE)

Lagadas county is located NE to the city of Thessaloniki, in northern Greece and has an area of about 200000 ha. The landscape is structured into different elevation zones from 35 to 1100 m a.s.l. Climate is semi-arid Mediterranean with cold winters. Geology is dominated by metamorphic rocks which result in acid soils and topography is gentle to rough. There is a variety of land use types with rangelands covering about 40% of the whole area. They are dominated by kermes oak (Quercus coccifera L.) shrublands with crown densities ranging from very open (<15% shrub cover) to very dense (>70% shrub cover). In these openings, grasslands or rain fed agricultural areas mainly used for cereal production are found. Therefore, rangelands of Lagadas provide two groups of forage: grass (herbaceous species) and browse (shrubs).

Rangelands are state owned areas but communally grazed by livestock. There were about 150000 goats and 106000 sheep in the county in the year 2000 (National Statistical Service of Greece, 2001). Both kinds of animals are mainly bred in pure flocks which are housed at night in sheds and graze in rangelands during the day. Sheds are located around the edge of the villages or away from them, but always within the village territory. Goats and sheep are both double-purpose animals, mainly raised for milk and secondarily for meat (kids or lambs).

Goats are the main animals using rangelands, especially shrublands because they can feed on both herbaceous species and shrubs. Grazing is done the whole year round but mainly in the winter, spring and autumn. During summer, goats usually graze on cereal stubble of the village territory or, rarely, are moving to rangelands of other territories located at higher elevations. In late winter to early spring, private arable fields sown with cereals (artificial pastures) are also used for grazing (Yakoulaki et al. 2005). In addition, animals are also fed with hay and concentrates during the periods of feed shortage, especially in the winter months (Yakoulaki et al. 2003). Sheep, on the contrary, are using rangelands partially; they mainly feed on artificial pastures and cereal stubble and use grasslands or large shrub openings in spring and autumn. In addition, they are fed with hay and concentrate almost the whole year round.

Goat and sheep husbandry is an important economic activity in Lagadas County. In 2005, there were 458 goat and 535 sheep farms that yielded a net income of 7870590 € and 8918100 € respectively. Almost 40% of this income was incurred by subsidies that farmers received from the European Union. Without these subsidies, the profit of farmers per goat or sheep would have been very low, even negative (Kitsopanidis et al. 2009).

Within the county, the study focused on Askos which is a typical village of the region with 4000 ha of rangelands. In 2005, goats and sheep amounted to about 7200 and 2000 heads respectively.

Data availability to be used to calibrate the model for this particular site were variable. Annual time-series data existed for rainfall and prices, but for most of the other variables and parameters there were only sparse data coming from either researches' databases or the literature. Finally, no quantitative information was available for a residual set of parameters.

Under these circumstances model's calibration proceeded by the following four stages:

i) Two sets of invariable time-trajectories representing benchmarks for the system were established for the main variables using the available information. One benchmark corresponded to an average scenario, and the other to one of exceptional high rainfall.

ii) Different values for each unknown parameter were tried iteratively, within plausible ranges, until the whole model was able to simulate both sets of time-trajectories in a robust and coherent way. That is, the whole model was taken as a unique function including unknown parameters and these were estimated, by means of repeated simulations, to make the model—the function—fit as much as possible and under their respective scenarios to the time-trajectories defining each benchmark.

iii) Once a preliminary complete set of parameter values was obtained, it was checked if the model behaved coherently under scenarios reflecting different extreme situations—e.g. long severe droughts or extremely high or low prices. If not, some of the parameter values were revised.

iv) Finally, model's behaviour was showed to experts who knew well the site. Different scenarios were analyzed with them in order to ensure their agreement with model's behaviour.

For illustration, the average benchmark for Askos was defined by one hectare with: 11000 kg of total shrub biomass; annual production of 2200 and 890 kg/year for shrubs and herbs, respectively; a potential herb production of 1900 kg/year, if the hectare were entirely emptied of shrubs; an initial soil depth of 450 mm, of which 230 mm corresponded to horizon A; a bedrock weathering rate of 0.26 mm/year; an erosion rate of 0.3 mm/year; a stocking rate of 0.57 animals (78% goats and 22 % sheep) of which 0.39 were rights; biomass utilization rates around 30%; an amount of supplemental feed of 327 kg/animal/year; a milk yield of 143 kg/animal/year and a gross margin of 50 €/animal/year of which 36 €/animal/year were subsidies. The unknown parameters had to be chosen for the model to reproduce this average benchmark situation under the invariable average-scenario where every exogenous variable was equated to its respective mean (Table 1).

TABLE 1

The calibration procedure showed that only a narrow range of values for each unknown parameter was suitable to make the model simulate the two benchmarks. In this way, calibration did not turn out to be a difficult task in this particular application and a satisfactory degree of confidence on the values finally obtained was achieved. Table 2 shows these values.

TABLE 2

Only one issue regarding the estimated parameters will be highlighted. Note that sbo = 33.6 meaning that the actual intake of energy per animal in Lagadas would be around a 34% above the optimum value. This means that most of the farmers will get improvements in gross margins if they significantly reduce supplemental feed. An excessive consumption of supplemental feed was also reported by Kitsopanidis et al. (2009).

To run the model under realistic scenarios where all of the exogenous variables change each year, their values are generated using a particular random-normal distribution for each one. Therefore, the mean and standard deviations of the four model's exogenous variables are needed. Those of *RNF*, *PRM* and *PRS* were calculated over their respective recorded time-series (n = 72, 22 and 46 years, respectively). The mean of *BSE* was an estimation based on the parent rock and the soil type of Lagadas site (D. Alifragis, personal communication). To estimate the standard deviation of this variable, bse_std, a survey of erosion rates (n = 16) corresponding to Askos, coming from the PESERA database (Kirkby et al. 2004), was used. Firstly, the frequency distribution of the recorded erosion rates was calculated. Secondly, bse_std was calibrated simulating the model repeatedly until the frequency distribution of the erosion rate, SER, corresponding to a long period of time resembled the recorded one —of course, under a scenario generated stochastically. Means and standard deviations of the exogenous variables are shown in table 1.

Figure 6 plots the time-trajectories of the main model's endogenous variables obtained by running the model 150 years under a scenario where random-normal values are annually generated for every exogenous variable, using their respective mean and standard deviations. Note that the time-trajectories oscillate around the values defining the average benchmark for the system, previously provided. This shows that the main objective of the calibration process was achieved. Moreover, near to 10 mm of soil are lost during the simulated time-period. This result seems to show that degradation through erosion exists in Lagadas though the process does not seem to be too fast. Nevertheless, a more detailed assessment of whether and why degradation could exist in Lagadas are made in the next section.

FIGURE 6

5.- ASSESING RANGELANDS' DEGRADATION RISKS IN LAGADAS

Analysing a set of model's equilibria

In order to assess rangeland degradation risks in Lagadas, 2000 groups of four values for the exogenous variables—*RNF*, *BSE*, *PRM* and *PRS*—were randomly generated using their respective normal distributions. As we already know, a different long-term equilibrium corresponds to each group so that 2000 annual equilibria were obtained. Figure 7 shows the scatter plot of such equilibria.

FIGURE 7

First of all, it must be mentioned that since scc = 4.8 10^{-5} ha/kg (see table 2) then 1/scc = 20833 kg/ha. This value, as well as msh = 220 (see table 2), allows to mark out in fig. 7 the grey (permanent degradation), the dotted (reversible degradation) and the white (no degradation) regions (recall fig. 5).

It is quite important to note that the highlighted point very close to the origin is repeated 888 times really. Therefore, contrary to what a first glance over the figure shows, a 44.85% of the equilibria are positioned within the grey region of permanent degradation. In turn, 52.9% of the equilibria are within the white region of no degradation and only 2.25% are within the dotted region of reversible degradation. In this way, we may initially quantify the risk of rangeland degradation through erosion in Lagadas as being near to 45% and the risk of degradation through shrub invasion—without erosion—as being around 2%.

As we know, both figures correspond to the possibility of the system to entirely lose herbaceous vegetation, what may be seen as a very extreme situation. However, if a greater threshold for the loss of herb production to mark out degradation is established, the risks do not change excessively. As an illustration, if we consider that the system is degraded whenever herb production is under a 40% of its benchmark value—i.e. when AHP < 356 kg/ha, a 40% of 890 kg/ha—the risk of degradation by shrub invasion turn to be of 11% while the risk of degradation by erosion remain unchanged.

The current system’s position is quite close to the average scenario’s equilibrium (see fig. 7). Where is it expected to move to in the future? Certainly, sustainable and degraded equilibria are near to be balanced—52% and 45%, respectively, with their original definition. In this way, degradation through erosion can not be rejected in Lagadas although its speed would not be high.

This is shown in fig. 8 which plots the time-trajectories of TSB and SOI obtained by running the model 4000 years under a stochastic scenario where random-normal values are generated for the exogenous variables each year—i.e. both time-trajectories are the same than those already showed in fig. 6 but considerably lengthened. Note that these time-trajectories associate to the cloud of annual equilibria in exactly the same way as the time-trajectory drawn in fig. 4 did to the four equilibria there exemplified.

FIGURE 8

It can be seen that only after around 3700 years both the shrub biomass and the soil would entirely disappear in the modelled hectare; for herb biomass (not shown in the figure), this would occur after around 3300 years. Therefore, the system could end up degraded through erosion, indeed, but the time for it to happen would be so long that the assessment becomes irrelevant.

Summarizing, as far as this research can reach, rangelands in Lagadas show at the present time a low risk of degradation by shrub invasion and a negligible risk of degradation by erosion.

Sensitivity analysis

What are the factors whose eventual change regarding the present situation would most likely make degradation risks to increase in Lagadas? To answer this question a model's sensitivity analysis has been carried out. Specifically, the Plackett-Burman technique for sensitivity analysis (PBSA) was used. Briefly—see Beres and Hawkins (2001) for details—this is a statistically sound procedure which measures the effects of each parameter on target output variables in an efficient way in terms of the number of scenarios needed. An important feature is the fact that the effects of every parameter are not measured under the all-other-things-being-equal assumption but are averaged over variations made in all other parameters.

To apply the PBSA technique, upper and lower values must be firstly assigned to each parameter of the model. The next step consists in designing 2d scenarios, where d is any multiple of 4 greater than the number of parameters n. Every scenario is made up of n parameter values which are sampled from the upper and lower ones previously assigned. The design of scenarios follows patterns, firstly proposed by Plackett and Burman (1946), that result in suitably allocating every lower value in d scenarios and every upper value in the remainder d scenarios. The effects of every parameter are obtained by adding up the 2d outputs of each target variable and then dividing by d.

In our case, the upper and lower values for every parameter, exogenous variables' means and standard deviations included, resulted from increasing/decreasing a 10% the default sets given in tables 1 and 2. Exceptions were the decoupling percentage, dps, which can only take the values 0, 0.5 and 1 so that 0 and 1 had to be selected, and the shrub-soil relation parameter, ss1, whose zero default-value does not allows applying any percentage; 10 and -10 mm were arbitrarily taken as its upper and lower values, respectively (recall fig. 1).

The PBSA's time-horizon to record the target variables was established at 100 years. Note that all the scenarios established within the procedure are simulated stochastically, since they include the means and the standard deviations of the exogenous variables. Therefore, in order to achieve a more robust analysis, 100 simulations were run under each scenario making the seed of the random-generator algorithm to take 100 different values. In this way, samples of size 100 were obtained for the state variables, SOI and TSB, with each scenario. Then, the means of SOI and TSB over these samples were used as the PBSA's target variables.

Table 3 shows the twenty most important parameters and their impacts on SOI and TSB. The impacts must be interpreted in the following way: 'a 10% of increase in parameter x produces a change of y units in the target variable z at year 100'. The sign of the score indicates the direction of the corresponding impact. Also, recall that benchmark values and units are 450 mm for SOI and 11000 kg/ha for TSB.

TABLE 3

Note that average annual rainfall is the factor with the greatest impact on both the soil and the shrubs. Thus, an eventual reduction in average rainfall would be the principal factor threatening rangelands in Lagadas to be degraded through erosion. Also, an eventual increase in average rainfall would be the most important factor favouring shrub invasion.

Other parameters importantly affecting soil depth at year 100 are those involved in determining the bedrock weathering rate (pwr and wsr) and the relations between rainfall and the annual productions of herbs and shrubs (phs, phi, mrr and sxs). Only three factors related to the stocking rate are included among the twenty most importantly affecting the soil: pbi, oca and prs_mean. Anyway, their impacts are certainly low or negligible—shifts of 10% in pbi, oca and prs_mean would produce the soil to vary at year 100 1.3%, 0.6% and 0.4%, respectively, regarding its current value. It follows that degradation through erosion could be accelerated in Lagadas if significant changes would occur in some abiotic factors; any eventual change in livestock numbers or biomass consumption hardly could affect erosion.

Regarding the growth of shrubs, again those parameters relating rainfall and shrub productivity (mrr, sxs, xsi) are between the most important ones. But the remarkable issue here is that many parameters related to livestock are now included between those most affecting the amount of shrub biomass at year 100. Indeed, pbi, bss and sfe are related to the biomass consumed per head and oca, prs_mean, ika, gm1 and sbh to livestock numbers.

Therefore, we can conclude that, at least in Lagadas, livestock in general, and factors increasing farmers' profitability in particular—i.e. advantageous prices and subsidies—would be helping to combat shrub invasion while having negligible impacts on erosion rates. However, more applications of the model to Mediterranean rangelands other than the ones found in Lagadas should be carried out in order to see whether such results can be generalized or not.

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REFERENCES

Abrahams, A.D.; Parsons, A.J.; Wainwright, J. 1999. Effects of vegetation change on interrill runoff and erosion, Walnut Gulch, southern Arizona. Geomorphology, 13: 37-48.

Anderies, J.M.; Janssen, M.A. and Walker, B.H. 2002. Grazing management, resilience and the dynamics of a fire-driven rangeland system. Ecosystems, 5: 23-44.

Beres, D. L., and D. M. Hawkins. 2001. Plackett-Burman technique for sensitivity analysis of many-parametered models. Ecological Modelling, 141: 171– 183.

Edelstein-Keshet, L. 1988. Mathematical models in biology. McGraw-Hill, New York.

Ellis, J.E. and Swift, D.M. 1988. Stability of African pastoral ecosystems: Alternate paradigms and implications for development. Journal of Range Management, 41 (6): 450-459.

Elwell, H.A. and Stocking, M.A., 1976. Vegetal cover to estimate soil erosion hazard in Rhodesia. Geoderma, 15: 61-70.

Grove, A. T.; Rackham, O. 2001. The nature of Mediterranean Europe: An ecological history, Yale University Press. London. 384 p.

Ibañez, J., Martínez, J., Puigdefábregas, J., 2008. Assessing desertification risk using system stability condition analysis. Ecological Modelling, 213: 180-190.

Kosmas, C.; Danalatos, N.; Cammeraat, L.H.; Chabart, M.; Diamantopoulos, J.; Farand, R.; Gutierrez, L.; Jacob, A.; Marques, H.; Martinez-Fernandez, J.; Mizara, A.; Moustakas, N.; Nicolau, J.M.; Oliveros, C.; Pinna, G.; Puddu, R.; Puigdefabregas, J.; Roxo, M.; Simao, A.; Stamou, G.; Tomasi, N.; Usai, D. and Vacca, A. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena, 29: 45-59.

Hardin, G. 1968. The tragedy of the commons. Science, 162(13): 1243-1247.

Illius, A.W. and O'Connor, T.G. 1999. On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. Ecological Applications, 9 (3): 798-813.

Kéfi, S.; Rietkerk, M.; Alados, C.L.; Pueyo, Y.; Papanastasis, V.P.; ElAich, A. de Ruiter, P.C. 2007. Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. Nature, 449, doi:10.1038/nature06111: 213-218.

Kirkby, M.J., Jones, R.J.A., Irvine, B., Gobin, A, Govers, G., Cerdan, O., Van Rompaey, A.J.J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S., Van Lynden, G.J. and Huting, J. 2004. "Pan-European Soil Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. Explanation of Special Publication Ispra 2004 No.73 (S.P.I.04.73)." European Soil Bureau Research Report

No.16, EUR 21176, 18pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

Kitsopanidis, G.; Zioganas, M.; Derva, E. and Papanastasis V.P. 2009. Profitability of sheep and goat farming systems in Lagadas county of Thessaloniki prefecture. Georgia-Ktinotrofia, 3: 60-70 (In Greek)

Kosmas, C.; Danalatos, N.; Cammeraat, L.H.; Chabart, M.; Diamantopoulos, J.; Farand, R.; Gutierrez, L.; Jacob, A.; Marques, H.; Martinez-Fernandez, J.; Mizara, A.; Moustakas, N.; Nicolau, J.M.; Oliveros, C.; Pinna, G.; Puddu, R.; Puigdefabregas, J.; Roxo, M.; Simao, A.; Stamou, G.; Tomasi, N.; Usai, D. and Vacca, A. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena, 29: 45-59.

Le Houérou, H.N. 1981. Impact of man and his animals on Mediterranean vegetation. In F.di Castri; D.W. Goodall and R.L. Specht (eds): Mediterranean – type shrublands, Ecosystems of the World 11. Elsevier Sci. Publ. Co. N.Y., p. 479-521.

Le Houérou, H.N. 1993. Land degradation in Mediterranean Europe: can agroforestry be a part of the solution? A prospective review. Agroforestry systems, 21: 43-61.

Mendizábal, T. and Puigdefábregas, J. 2003. Population and land use changes: impacts on desertification in Southern Europe and in the Maghreb. In Brauch, H.G.; Liotta, P.H.; Marquina, A.; Rogers, P.F.; Selim, M.E.-S. (Eds.): Security and Environment in the Mediterranean Conceptualising Security and Environmental Conflicts. Series: Hexagon Series on Human and Environmental Security and Peace, Springuer, Vol. 1: 687-701

National Statistical Service of Greece. 2001. Results of the agricultural – livestock census 1999/2000. www.statistics.gr (In Greek)

Noy-Meir, I. 1975. Stability on grazing systems: an application of predator-prey graphs. Journal of Ecology, 63: 459-481.

Oesterheld, M.; Sala, O.E. and McNaughton, S.J. 1992. Effect of animal husbandry on herbivore-carrying capacity at a regional scale. Nature, 356. 234-236.

Papanastasis, V. 1993. Legal status of land tenure and use and its implication for open landscapes of western Crete. Landscape and Urban Planning, 24: 273-277.

Papanastasis, V. P. and P. Mansat. 1996. Grasslands and related forage resources in Mediterranean areas. In G. Parente; J. Frame and S. Orsi (eds): Grasslands and Land Use Systems. Grassland Science in Europe, Vol. 1: 47-57.

Papanastasis, V.P. and Kyriakakis, S. 2003. Plant cover as a tool for monitoring desertification in mountain Mediterranean rangelands. Management of Environmental Quality: An International Journal, 14 (1): 69-81.

Perevolotsky, A. and Seligman, N. G. 1998. Role of grazing in Mediterranean rangeland ecosystems. BioScience, 48 (12): 1007-1017.

Plackett, R. L. and J. P. Burman. 1946. The design of optimum multifactorial experiments. Biometrica, 33: 305– 325.

Rietkerk, M. and van de Koppel, J. 1997. Alternate stable states and threshold effects in semi-arid grazing systems. Oikos. Vol 79: 69-76.

Röder, A.; Knemmerle, T.; Hill, J.; Papanastasis, V.P. and Tsiourlis, G.M. 2007. Adaptation of a grazing gradient concept to heterogeneous Mediterranean rangelands using cost surface modelling. Ecological Modelling, 204: 387-398.

Rowntree, K.; Duma, M.; Kakembo, V. and Thornes, J. 2004. Debunking the myth of overgrazing and soil erosion. Land Degradation and development, 15: 203-214.

Schlesinger, W.H.; Reynolds, J.F.; Cunningham, G.L.; Huenneke, L.F.; Jarrell, W.M.; Virginia, R.A. and Whitford, W.G. 1990. Biological feedbacks in global desertification. Science, 247: 1043-1048.

Sharma, K.D. 1998. The hydrological indicators of desertification. Journal of Arid Environments. Vol 39 (2): 121-132.

Soyza, A. G.; Whitford, W. G.; Herrick, J. E.; Van Zee, J. W. and Havstad, K. M. 1998. Early warning indicators of desertification: examples of tests in the Chihuahuan Desert. Journal of Arid Environments. Vol 39 (2): 101-112.

Sullivan, S. and Rohde, R. 2002. On non-equilibrium in arid and semi-arid grazing systems. Journal of Biogeography, 29: 1595-1618.

Veron, S.R.; Paruelo, J.M. and Oesterheld, M. 2006. Assessing desertification. Journal of Arid Environments. Vol 66 (4): 751-763.

Walker, B. H.; Ludwig, D.; Holling, C.S. y Peterman, R.M. 1981. Stability of semi-arid savanna grazing systems. Journal of Ecology. Vol 69 (2): 473-498.

Walker, B. 1993. Rangeland ecology: Understanding and managing change. Ambio, 22 (2-3): 80-87.

Wilson, A.D. and Macleod, N.D. 1991. Overgrazing: Present or absent? Journal of Range Management, 44 (5): 475-482.

Yiakoulaki, M.D., M.P. Zarovali, I. Ispikoudis and V.P. Papanastasis. 2003. Evaluation of small ruminants' production systems in the area of Lagadas county, Greece. Proceedings of the 3rd Conference of the Hellenic Range and Pasture Society, Karpenisi Greece, 4-6 September 2002 (in Greek, English summary). p.395-402.

Yiakoulaki, M.D., Ch. I. Pantazopoulos and V.P.Papanastasis. 2005. Sheep and goat behaviour grazing on stabble in northern Greece. In: Animal Production and Natural Resources Utilization in the Mediterranean Mountain Areas (A. Georgoudis, A. Rosati and C. Mosconi, eds) EAAP Publication No. 115. Wageningen Academic Publishers, The Netherlands. p. 216-219.

LISTS OF VARIABLES AND PARAMETERS

ENDOGENOUS VARIABLES		
NAME	**DEFINITION [equation number where defined]**	**UNITS**
ABP	Available biomass [23]	[kg ha^{-1} a^{-1}]
AHP	Aboveground herb production [9]	[kg ha^{-1} a^{-1}]
ASP	Aboveground shrub production [2]	[kg ha^{-1} a^{-1}]
BEC	Biomass average energy content [33]	[FU kg^{-1}]
BWR	Bedrock weathering rate [15]	[mm a^{-1}]
GHB	Ungrazed aboveground herb biomass [8]	[kg ha^{-1} a^{-1}]
GMA	Gross margin per animal [20]	[€ AU^{-1} a^{-1}]
GMA^{e}	Estimated gross margin per animal [19]	[€ AU^{-1} a^{-1}]
HCR	Herb biomass consumption rate [25]	[kg ha^{-1} a^{-1}]
HBA	Herb biomass consumed per animal [26]	[kg AU^{-1} a^{-1}]
HPA	Herb proportion in biomass consumed per animal [27]	[dmnl]
IEA	Intake of energy per animal [35]	[FU AU^{-1} a^{-1}]
IEA^{o}	Optimum intake of energy per animal [34]	[FU AU^{-1} a^{-1}]
MYA	Milk yield per animal [21]	[kg AU^{-1} a^{-1}]
NBA	New-biomass consumed per animal [24]	[kg AU^{-1} a^{-1}]
NSA	New shrub biomass consumed per animal [29]	[kg AU^{-1} a^{-1}]
OMR	Organic matter deposition rate [16]	[mm a^{-1}]
OSA	Old shrub biomass consumed per animal [30]	[kg AU^{-1} a^{-1}]
PHP	Potential herb production [11]	[kg ha^{-1} a^{-1}]
PSP	Potential aboveground shrub production [3]	[kg ha^{-1} a^{-1}]
RBA	Required biomass per animal [22]	[kg AU^{-1} a^{-1}]
SFA	Supplemental feed consumed per animal [31]	[kg AU^{-1} a^{-1}]
SFA^{t}	Target supplemental feed consumed per animal [32]	[kg AU^{-1} a^{-1}]
SFA^{x}	Extra supplemental feed consumed per animal [36]	[kg AU^{-1} a^{-1}]
SCR	Shrub biomass consumption rate [28]	[kg ha^{-1} a^{-1}]
SDR	Shrub biomass death rate [7]	[kg ha^{-1} a^{-1}]
SER	Soil erosion net-rate [17]	[mm a^{-1}]
SKR	Stocking rate [18]	[AU ha^{-1}]
SOI	Soil depth [14]	[mm]
SPH	Soil productivity factor for herbs [10]	[dmnl]
SPS	Soil productivity factor for shrubs [6]	[dmnl]
SSM	Subsoil moisture [5]	[mm]
TSB	Total aboveground shrub biomass [1]	[kg ha^{-1}]
XSP	Maximum potential aboveground shrub production [4]	[kg ha^{-1} a^{-1}]
EXOGENOUS VARIABLES		
NAME	**DEFINITION [equation numbers where used]**	**UNITS**
BSE	Bare soil erosion rate [17]	[mm a^{-1}]
PRM	Price of milk [20,34]	[€ kg^{-1}]
PRS	Price of supplemental feed [20, 34]	[€ kg^{-1}]
RNF	Rainfall [5, 11]	[mm a^{-1}]

PARAMETERS		
NAME	**DEFINITION [equation numbers where used]**	**UNITS**
bss	Biomass-supplement substitution coefficient [22, 32, 34]	[dmnl]
dps	Decoupling percentage of payments [18]	[dmnl]
ehr	Erosion-herb biomass relation parameter [17]	[ha a kg^{-1}]
esr	Erosion-shrub biomass relation parameter [17]	[ha kg^{-1}]
fod	Fractional organic matter decomposition rate [16]	[dmnl]
fsd	Fractional shrub biomass death rate [7]	[a^{-1}]
gm1	Gross margin per animal that makes SKR to be one [18]	[€ ha AU^{-2} a^{-1}]
gma_i	Gross margin per animal, initial value for smoothing [19]	[€ AU^{-1} a^{-1}]
gma_t	Gross margin per animal, adjustment time for smoothing [19]	[a]
hec	Herb energy content [33, 36]	[FU kg^{-1}]
hpr	Consumed-available herb proportions relation parameter [27]	[dmnl]
hsr	Herb-soil relation parameter [10]	[mm]
ika	Income from the selling of kids per animal [20]	[€ AU^{-1} a^{-1}]
mdc	Mass to depth unit conversion coefficient for organic matter [16]	[mm ha kg^{-1}]
mer	Milk-energy intake relation parameter [21, 34]	[AU a FU^{-1}]
mrr	Moisture-rainfall relation parameter [5]	[a]
msh	Minimum soil depth for herb production [10]	[mm]
oca	Other cost per animal (not supplemental feed) [20]	[€ AU^{-1} a^{-1}]
oma	Organic matter per animal [16]	[kg AU^{-1} a^{-1}]
pbi	Biomass intake per animal without supplemental feed [22, 32]	[kg AU^{-1} a^{-1}]
peh	Proportion of eatable herb production [23, 27]	[dmnl]
pen	Proportion of eatable shrub production [23]	[dmnl]
pes	Proportion of eatable total shrub biomass [28]	[dmnl]
phi	Potential herb production-intercept [11]	[kg ha^{-1} a^{-1}]
phs	Slope of the linear equation in the potential herb production and *RNF* [11]	[kg ha^{-1} mm^{-1}]
pmy	Potential milk yield per animal [21, 34]	[kg AU^{-1} a^{-1}]
pwr	Potential bedrock weathering rate [15]	[mm a^{-1}]
rgh	Subsidized animals (rights) in the hectare [18]	[AU ha^{-1}]
rnf_i	Rainfall, initial value for smoothing [5]	[mm a^{-1}]
rnf_t	Rainfall, adjustment time for smoothing [5]	[a]
sbh	Total subsidies to the hectare [20]	[€ ha^{-1} a^{-1}]
sbo	Rate of systematic bias from optimum energy intake per animal [35]	[dmnl]
scc	Shrub biomass to cover percentage conversion coefficient [9, 17]	[dmnl kg^{-1} ha^{-1}]
sec	Shrub energy content [33, 36]	[FU kg^{-1}]
sfe	Supplemental feed energy content [32, 34, 36]	[FU kg^{-1}]
spt	Slope of the linear equation in the potential aboveground shrub production and TSB [3]	[a^{-1}]
ss1	Shrub-soil relation parameter 1 [6]	[mm]
ss2	Shrub-soil relation parameter 2 [6]	[mm]
sxs	Slope of the linear equation in the maximum potential aboveground shrub production and SSM [4]	[kg ha^{-1} a^{-1} mm^{-1}]
wsr	Weathering-soil depth relation parameter [15]	[a^{-1}]
xsi	Maximum potential aboveground shrub production-intercept [4]	[kg ha^{-1} a^{-1}]

1220

Figure

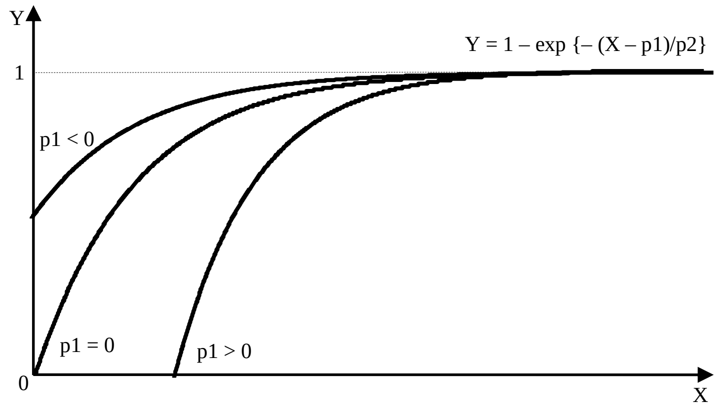

Fig. 1 – Shapes of the inverted exponential functional form when three different values are assigned to one of its parameters

Figure

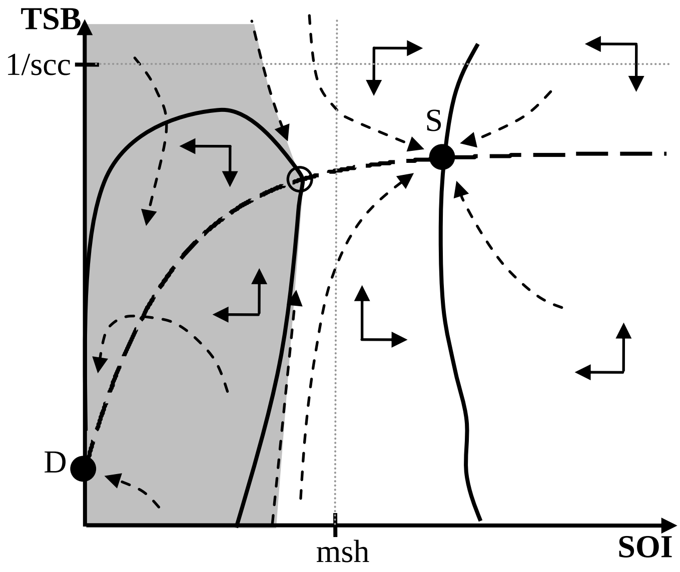

Fig. 2 – An instance (case A) of the relevant dynamic elements of the model (explained in the text) where sustainability is likely

Figure

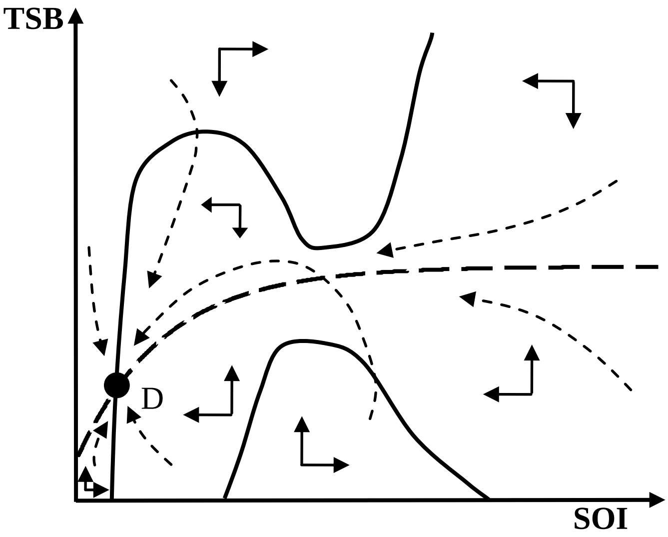

Fig. 3 – An instance (case B) of the model's nullclines corresponding to degradation

Figure

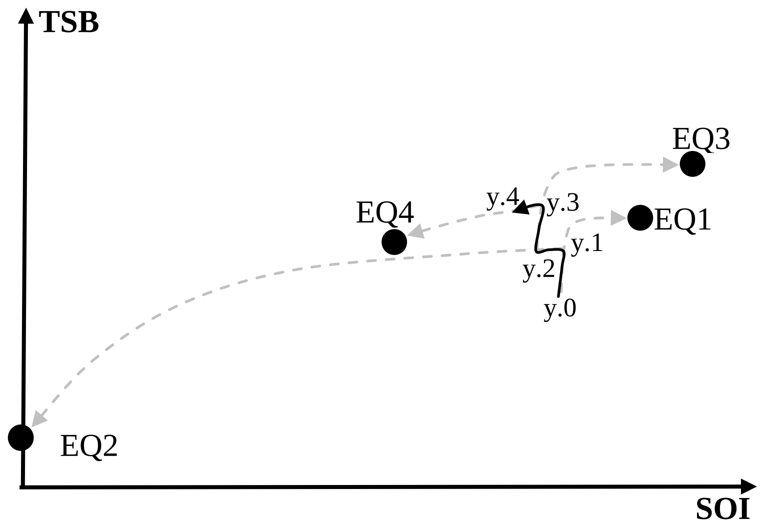

Fig. 4 – Equilibrium points, time-trajectories which would lead to every equilibrium if the exogenous variables were fixed to their current values from the corresponding year on (dashed arrows) and actual time-trajectory (solid arrow) corresponding to the following series of four years: average (y.1), severely dry with some torrential storms (y.2), humid (y.3) and moderately dry (y.4)

Figure

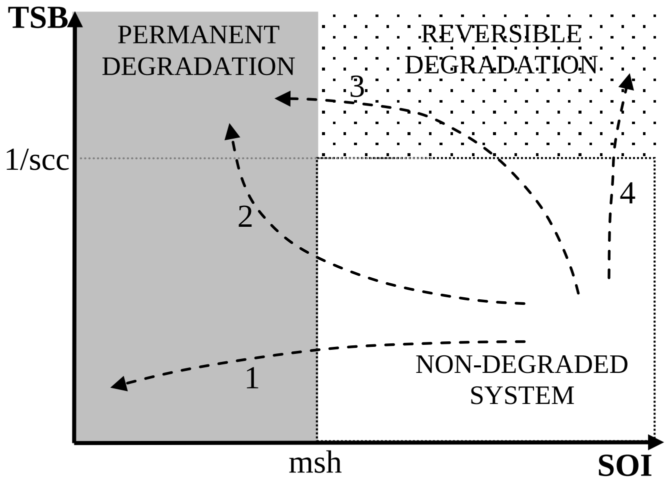

Fig. 5 – The phase plane's regions associated with a non-degraded rangeland (white), permanent degradation (grey) and reversible degradation (dotted) and different tendencies towards degradation (dashed arrows)

Figure

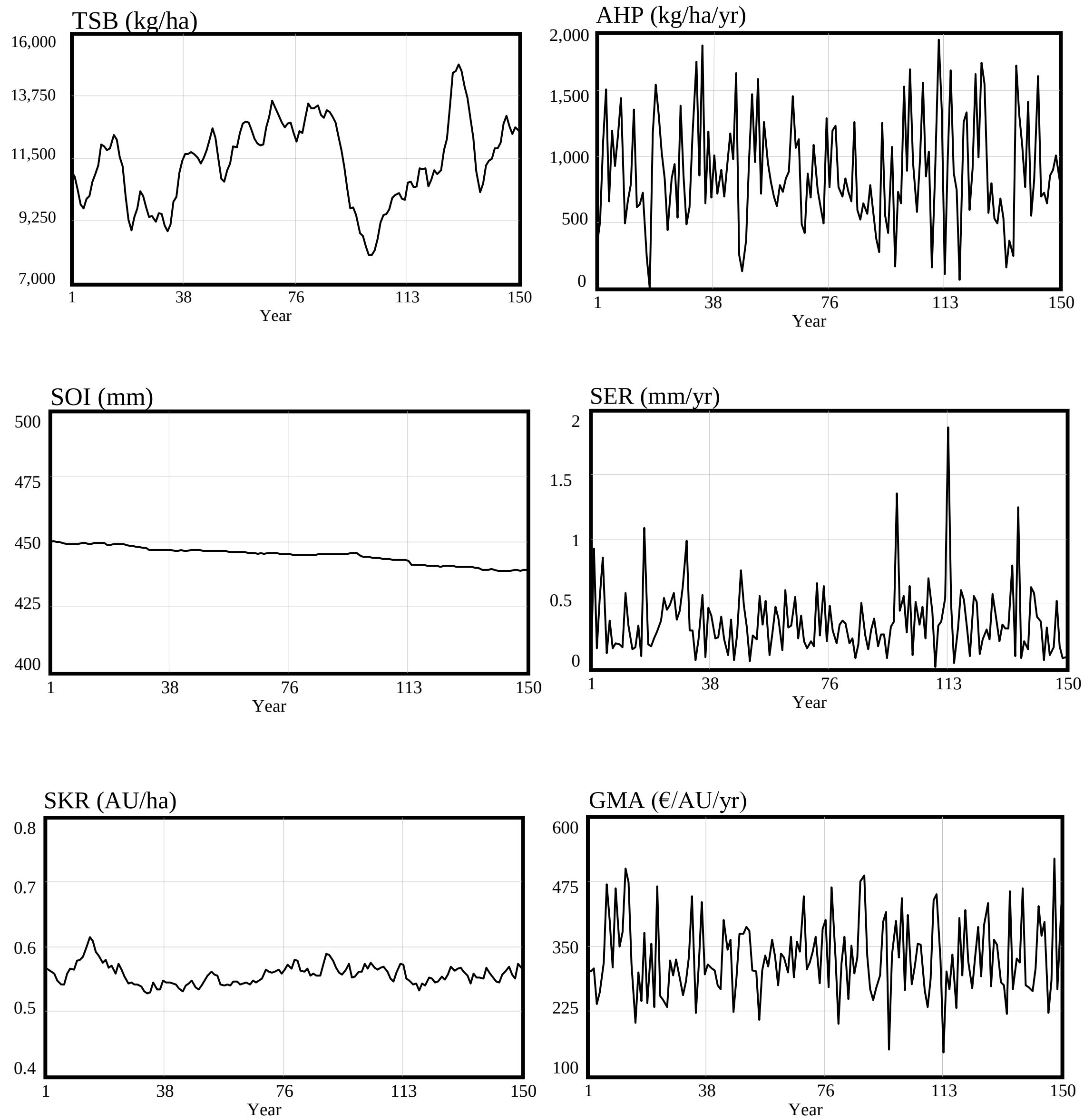

Fig. 6 – Time-trajectories of total shrub biomass (TSB), annual herb production (AHP), soil depth (SOI), erosion rate (SER), stocking rate (SKR) and gross margin per animal (GMA) under a scenario of random-normal values generated for the exogenous variables

Figure

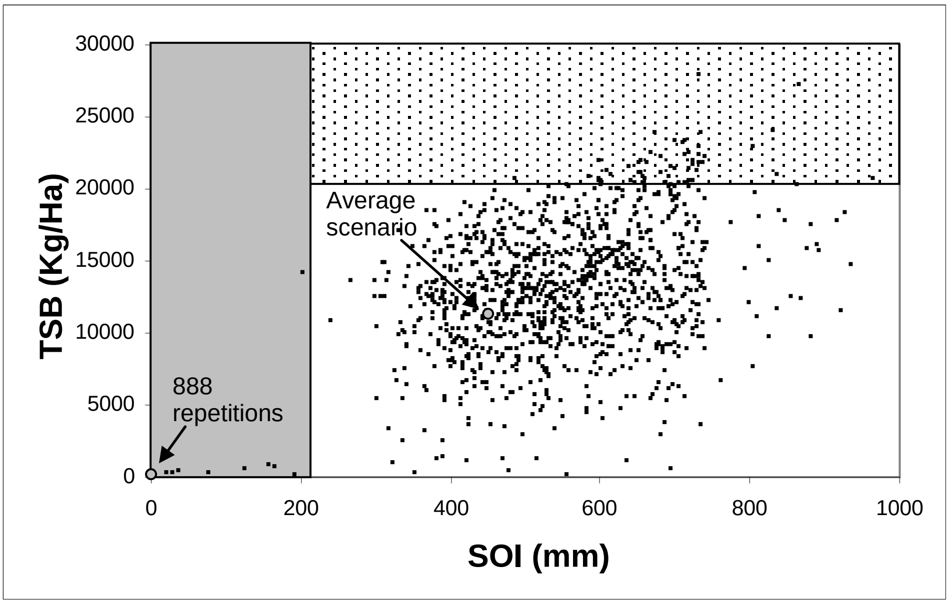

Fig. 7 – Cloud of 2000 annual equilibria corresponding to the same number of groups of four values generated for the exogenous variables from their random-normal distributions

Figure

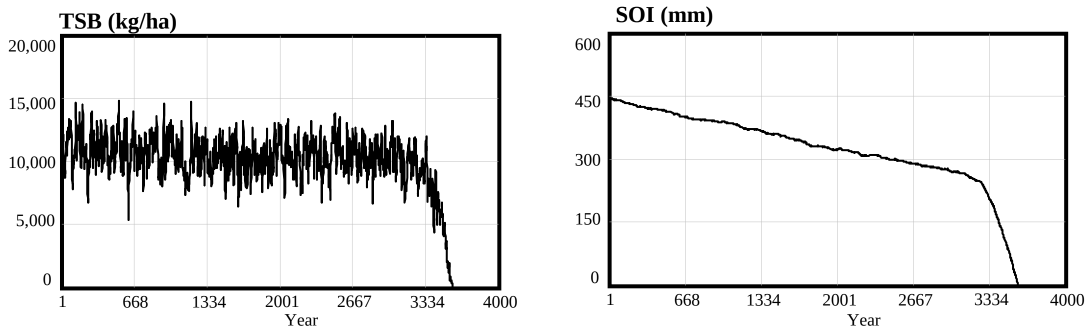

Fig. 8 – Lengthened time-trajectories of total shrub biomass (TSB) and soil depth (SOI) under a scenario of random-normal values generated for the exogenous variables

Tables

EXOGENOUS VARIABLE	MEAN	STANDARD DEVIATION
RNF	rnf_mean = 485 mm	rnf_std = 112 mm/year
BSE	bse_mean = 1.6 mm/year	bse_std = 1 mm/year
PRM	prm_mean = 0.65 €/kg	prm_std = 0.105 €/kg
PRS	prs_mean = 0.143 €/kg	prs_std = 0.006 €/kg

Table 1.- Means and standard deviations of the exogenous variables

Tables

bss	0.38 [dmnl]	pen	0.8 [dmnl]
dps	0.5 [dmnl]	pes	0.6 [dmnl]
ehr	0.003 ha a kg^{-1}	phi	1791.4 kg ha^{-1} a^{-1}
esr	0.00014 ha kg^{-1}	phs	7.61 kg ha^{-1} mm^{-1}
fod	0.85 [dmnl]	pmy	1600 kg AU^{-1} a^{-1}
fsd	0.14 a^{-1}	pwr	0.65 mm a^{-1}
gm1	588.57 € ha AU^{-2} a^{-1}	rgh	0.39 AU ha^{-1}
gma_i	334 € AU^{-1} a^{-1}	rnf_i	485 mm a^{-1}
gma_t	15 a	rnf_t	3 a
hec	0.5 FU kg^{-1}	sbh	136 € ha^{-1} a^{-1}
hpr	1 [dmnl]	sbo	0.336 [dmnl]
hsr	60 mm	scc	4.8×10^{-5} ha kg^{-1}
ika	375 € AU^{-1} a^{-1}	sec	0.3 FU kg^{-1}
mdc	5.7×10^{-5} mm ha kg^{-1}	sfe	0.892 FU kg^{-1}
mer	0.00036 AU a FU^{-1}	spt	0.0746 a^{-1}
mrr	0.14 a	ss1	0 mm
msh	220 mm	ss2	100 mm
oca	590 € AU^{-1} a^{-1}	sxs	69.41 kg ha^{-1} a^{-1} mm^{-1}
oma	1501 kg AU^{-1} a^{-1}	wsr	0.00087 a^{-1}
pbi	2462 kg AU^{-1} a^{-1}	xsi	1630.6 kg ha^{-1} a^{-1}
peh	0.8 [dmnl]		

Table 2.- Calibrated parameter values

PARAMETER	EFFECTS ON SOI (mm)	PARAMETER	EFFECTS ON TSB (kg/ha)
rnf_mean	19.12	rnf_mean	4191.61
pwr	12.15	mrr	3967.80
phs	11.55	sxs	3895.31
wsr	-7.67	xsi	-1398.47
phi	-7.29	fsd	-1378.18
mrr	6.62	pbi	-1268.42
sxs	6.16	spt	-716.65
pbi	-6.01	oca	604.52
bse_mean	-5.64	prs_mean	-484.76
esr	4.48	ika	-409.10
ehr	3.24	gm1	399.96
hpr	3.19	bss	349.58
scc	-3.08	phs	300.37
fod	-2.86	sbh	-288.43
peh	-2.82	sec	-208.18
oca	2.80	hpr	-199.67
xsi	-2.70	sfe	187.77
bse_std	-2.55	phi	-181.98
pen	2.42	hec	-176.90
prs_mean	-1.87	scc	-161.02

Table 3.- The greatest average impacts on soil depth (SOI) and total shrub biomass (TSB) at year 100 after increasing every parameter a 10%