LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.2165

A MULTIDISCIPLINARY MODEL FOR ASSESSING DEGRADATION IN MEDITERRANEAN RANGELANDS

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Received: 28 March 2011; Revised: 21 March 2012; Accepted: 6 April 2012

ABSTRACT

This paper presents an annual multidisciplinary, non-spatial model which formalizes the relationships linking the dynamics of shrubs, herbs, soil, livestock and farmers' behaviour with possible exogenous drivers of degradation, such as weather and prices. The model does not represent a pasture–livestock system but a shrub–soil one and is applied to a rangeland in Lagadas County (Northern Greece). A sensitivity analysis of the model is also presented. It shows that livestock, in general, and factors increasing farmers' profits, in particular, are currently helping to combat shrub invasion in Lagadas while having low impacts on erosion rates. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: rangeland modelling; economic–ecological model; shrub invasion; soil erosion; desertification drivers; sensitivity analysis; Greece

INTRODUCTION

Mediterranean rangelands are important natural resources with an area amounting to 48 per cent of the whole Mediterranean zone (Le Houerou, 1981). They are composed of several vegetation types including grasslands, shrublands and forests. Of these, grasslands have a limited area of no more than 20 per cent of the total (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 used by domestic animals, especially sheep and goats.

Two degradation processes are commonly pointed-out as affecting Mediterranean rangelands, overgrazing and undergrazing. The former may be defined as the progressive reduction of rangeland's productive capacity by overexploitation of primary production by livestock. Factors favouring overgrazing are (i) the communal system of use, where farmers would seek only short-term benefits, that is, Hardin's 'tragedy of commons' situation (Hardin, 1968); (ii) the large livestock numbers maintained by supplementing feed (e.g. Wilson and Macleod, 1991) and water (e.g. Röder *et al.*, 2007) and by improving the animals' health status (e.g. Oesterheld *et al.*, 1992); and (iii) subsidies, which would reinforce point (ii) (e.g. Papanastasis, 1993).

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For overgrazing to cause degradation, it must trigger some physical process or processes within the rangeland. In this case, erosion is the most widely reported. The common pattern of degradation is clear: Livestock reduce vegetation cover, thereby favouring runoff and the loss of soil by erosion. Soil storage capacity and the stocks of seeds and nutrients decline, thus hampering plant reproduction and growth. Another process that could lead to degradation of rangelands consists of a positive feedback between herbaceous cover and infiltration (Walker *et al.*, 1981; Rietkerk and van de Koppel, 1997). As soil is more exposed under grazing, surface pores are sealed, thereby reducing infiltration and thus available soil moisture, which further reduces plant cover. However, there are far fewer studies considering this process as the cause of degradation compared with erosion.

There is a controversy about 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) versus non-equilibrium (e.g. Ellis and Swift, 1988; Sullivan and Rohde, 2002) theories, although the latter is mainly focused on African rangelands. The following question summarizes the debate in a few words: Is permanent degradation in rangelands mainly driven by abiotic factors, that is, climate, or by management?

Those who doubt that Mediterranean rangelands are threatened by overgrazing claim that, in spite of having 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). This is supported by some studies showing that erosion rates in Mediterranean rangelands are not critical (Kosmas *et al*., 1997; Papanastasis and Kyriakakis, 2003).

Undergrazing is the other degradation process that is pointed out as threatening Mediterranean rangelands (Perevolotsky and Seligman, 1998; Le Houerou, 1993). It is characterized by the accumulation of woody biomass resulting in both lower grazing capacity and higher fire risk. Erosion in bare intershrub patches has also been reported in shrub-dominated rangelands (Schlesinger *et al*., 1990; Abrahams *et al*., 1999). It is argued that grazing is the only practical way to avoid the 'green deserts' created by undergrazing (Perevolotsky and Seligman, 1998), which is exactly the opposite recommendation to combat overgrazing.

This paper presents a model specifically designed for assessing degradation in Mediterranean rangelands. It explicitly reflects that the dynamics of soil and woody biomass signal the two possible processes of degradation, as the previous paragraphs have shown. Thus, the model does not formalize a livestock–pasture dynamic system, as usual, but a shrub–soil one. Nevertheless, herbs, livestock, farmers' behaviour and possible exogenous drivers of degradation (weather, subsidies and prices) are also represented in the model.

Model construction was developed within the DeSurvey Project, whose goal was to deliver a compact set of integrated procedures of desertification assessment and forecasting (www.desurvey.eeza.csic.es). Within the Project, Main Product 3 was concerned with assessing the sustainability of different land uses. The core of the Product was a generic desertification model linking climatic and socioeconomic drivers with the dynamics of natural resources (Ibañez *et al*., 2008). This generic model was customized to different case studies around the world, among them, the one presented here.

The second section of this paper is devoted to describe the model. Calibration for Askos, a village within Lagadas County (Northern Greece), is explained in the third section. A sensitivity analysis of the model, allowing ranking of potential degradation drivers in this particular case-study, is presented and commented in the fourth section. Finally, in the fifth section, there is a brief discussion on the methodology employed.

A MODEL FOR A COMMUNAL EU MEDITERRANEAN RANGELAND

The model described in the succeeding paragraphs represents an unspecified communal rangeland grazed by sheep and goats in a Mediterranean EU country. This rangeland consists of evergreen shrubs with herbaceous species growing among them. The model is based on annual data referred to the end of the dry season (summer) and is normalized to 1 ha. Therefore, its variables are expressed 'per hectare' and 'per year' although not always explicitly specified.

The model represents only above ground biomasses of both shrubs and herbs; this is not repeatedly mentioned throughout model description either. Below-ground biomass is not included in the model because of the lack of reliable data for calibration. Thus, it is assumed that below-ground biomass is enough to allow the above ground one to restart growing at any time. Anderies *et al*. (2002) and Higgins *et al*. (2007) included both above ground and below-ground biomass in their models, but they do not calibrate them to any real case studies.

Throughout the paper, variables are denoted by capital letters and parameters by lowercase letters. The difference between exogenous variables and parameters should be stressed. Both do not have equations in the model. However, in our case, the values the former took over time in simulations were generated by sampling from adequate random variables. Parameters are particular types of exogenous variables that are assumed not to vary over time. As such, every one of them took a single constant value in every simulation.

Model Overview

Figure 1 shows a non-exhaustive diagram of the fundamental relationships considered in the model. Soil depth and shrub

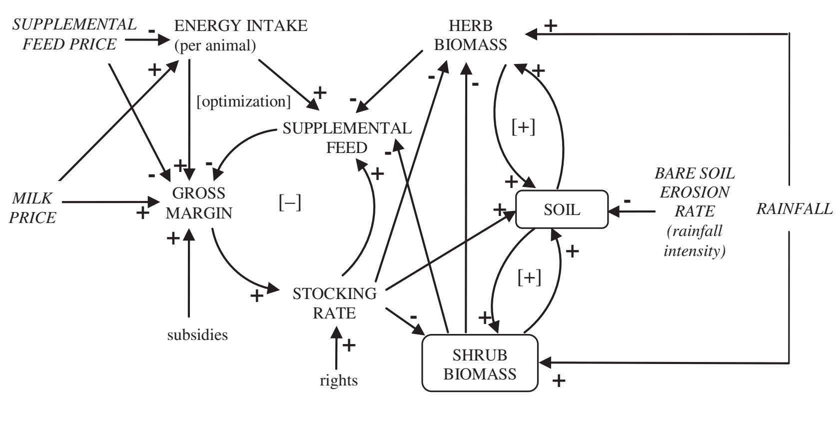

Figure 1. Diagram of the fundamental relationships in the model.

biomass are the two state variables (in rectangles). Annual rainfall, bare soil erosion rate (which is associated with rainfall intensity) and prices of milk and supplementary feed are the exogenous variables (italicized capitals). Subsidies and the number of subsidized animals, or 'rights', are included in the parameter set (lowercase letters).

Soil forms two positive feedback loops with the biomass of herbs and shrubs, which could cause degradation through erosion in simulations. Thus, if biomass decreased, soil would become thinner by erosion, thereby negatively affecting biomass in the long run.

A unidirectional relationship is established between shrub and herb biomasses: If the former increased, the latter would decrease, and the reverse is not possible. This could cause degradation by shrub invasion in simulations.

Livestock negatively affects biomass, through consumption, and positively affects soil formation, through deposition of manure. The stocking rate is positively related to rights and also to the gross margin obtained per animal. A negative feedback loop is established involving the stocking rate, supplementary feeding and gross margin: The higher the stocking rate, the larger the amount of supplementary feed needed and then the lesser the gross margins, all other things being equal.

Farmers decide the target energy intake of the animals. For that, they must consider the scenario for milk and supplementary feed prices and deal with an optimization problem. Indeed, increasing the energy intake positively affects yields, and thus gross margins, but also makes more supplementary feeding necessary, all other things being equal, thereby negatively affecting gross margins.

Henceforth, a detailed, section-by-section description of the model is provided.

Shrubs

The annual rate of variation of total (above ground) shrub biomass is given by:

$$\mathrm{d}TSB/\mathrm{d}t = ASP - SDR - SCR \tag{1}$$

Where: TSB is the total shrub biomass, *ASP* is the annual production of shrub biomass, or new browse, *SDR* is the rate of loss by death and *SCR* is the shrub biomass consumption rate.

The annual production of shrub biomass (*ASP*) is given by:

$$ASP = PSP \times (1 - \exp\{-(SOI - ss1)/ss2\}) \tag{2}$$

Where: PSP is the potential production of shrub biomass for the current year and for a hectare with enough soil depth (*SOI*); *ss*1 and *ss*2 are shrub–soil parameters. It is difficult to find a formal representation of the positive relationship between soil depth and biomass production in the literature. The inverted exponential function used in Equation 2 (Figure 2) is inspired by the soil profile model of Kirkby

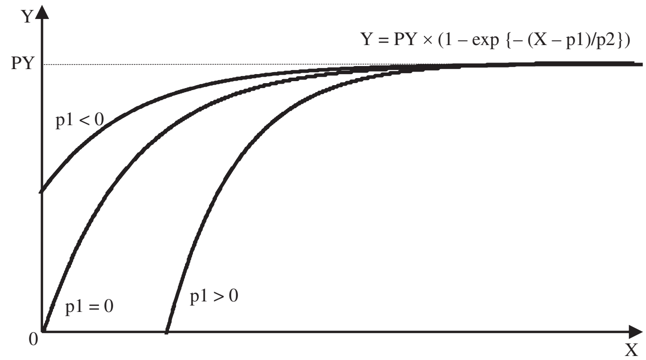

Figure 2. The generic form of the inverted exponential function: *Y* is the explained variable; *X* is the explanatory variable; *p*1 and *p*2 are parameters; *PY* is the potential value of *Y*, only reached if *X* is high enough. This function is particularized to three different cases in Equations 2, 8 and 17.

(1985). Note that a negative value of *ss*1 would mean that some shrub biomass would exist even though the soil would vanish (Figure 2). This is observed in some species of shrubs that grow roots in cracks to ensure the supply of nutrients and water (Grove and Rackham, 2001).

The potential production of shrub biomass (*PSP*) is given by:

$$PSP = \max\{0, XSP - spt\,TSB\} \tag{3}$$

Where: XSP is the maximum potential production of shrub biomass in the hectare and *spt* is a parameter. *XSP* depends on subsoil moisture, as will be shown soon. Otherwise, the potential production of shrub biomass decreases as the total shrub biomass (*TSB*) grows, because of competition. Linearity is assumed in Equation 3. This implies overestimating the potential new browse for a given soil depth when *TSB* is low and, particularly, assuming that maximum production occurs when there is no shrub biomass over the hectare, that is, when $TSB = 0$. Certainly, a concave function, showing a maximum at some intermediate value of *TSB*, would be more appropriate (e.g. Walker *et al*., 1981). However, two pragmatic reasons made us opt for linearity: (i) specific field data suitable for calibrating any non-linearity were lacking; (ii) as will be shown later on, the only factor causing *TSB* to reach low values in our assessments was severe losses of soil, which would result in a drastic reduction of the annual shrub production (*ASP*) by means of the second multiplier in Equation 2, thus alleviating the importance of overestimating the first one (*PSP*).

The maximum potential production of shrub biomass (*XSP*) linearly depends on subsoil moisture (*SSM*):

$$XSP = \max\{0, sxs \times SSM - xsi\} \tag{4}$$

In this equation, *sxs* is the slope and the *y*-intercept (*xsi*) has a negative sign to reflect that no productivity is possible below some minimum moisture. Sullivan and Rohde (2002, p. 1597) cited 12 references supporting a linear relationship such as in Equation 4, but with annual rainfall being used instead of subsoil moisture. The latter was preferred in our case because its slower dynamics would favour shrubs over herbs in dry periods, thereby significantly affecting the interaction between both plant types (e.g. Walker *et al*., 1981). However, including a detailed representation of subsoil moisture (*SSM*) would complicate the model considerably. As a tentative, intermediate solution, this variable was taken to be proportional to the exponential smoothing of annual rainfall (*RNF*):

$$SSM = mrr \times smoothi\{RNF, rnf_t, rnf_i\} \tag{5}$$

Exponential smoothing is a well-known technique. Its mathematical expression, here denoted by '*smoothi*', is shown in a footnote[1]. It includes two parameters, which are called rnf_t and rnf_i in this particular case. The third parameter in Equation 5, *mrr*, is a proportionality coefficient. Exponential smoothing yields a weighted moving average of past figures of a variable, here rainfall, where weights decrease exponentially as they go back over time. This provides subsoil moisture with an inertial behaviour in the model so that it does not entirely disappear unless a number of consecutive years without rainfall are simulated.

The rate of loss of shrub biomass by death (*SDR*) is given by:

$$SDR = fsd \times TSB \tag{6}$$

Where: TSB is total shrub biomass and *fsd* is the fractional death rate. A similar relationship was assumed by Walker *et al*. (1981) and Beukes *et al*. (2001).

Herbs

Pasture in the model is also composed of herbaceous species. It was assumed that both annual and perennial herbs dry out at the end of the growing season (end of spring) and start growing again the next season (autumn) from seeds or roots. As only above ground biomasses were represented, as indicated previously, no state or stock variable was used in this section of the model.

The equation for the ungrazed herb biomass at the end of the dry season (*GHB*) is:

$$GHB = AHP - HCR \tag{7}$$

Where: AHP is the annual herb production and *HCR* is the consumption rate. The former is given by:

$$AHP = PHP \times \max\{0, 1 - scc \times TSB\} \times (1 - \exp\{-\max\{0, SOI - msh\}/hsr\}) \tag{8}$$

Where: PHP is the potential herb production for the current year and for a hectare without shrubs ($TSB = 0$) and with enough soil depth. The first multiplier in Equation 8 (the max function) is the fraction of the hectare not covered by shrub biomass, which is the only area where herbs can grow. Therefore, *scc* is a coefficient to convert shrub biomass to cover percentage. Note that, regarding this first multiplier, herb biomass completely vanishes whenever *TSB* is equal to, or greater than, 1/*scc*.

The product of *PHP* times the first multiplier yields the potential herb production within the fraction of the hectare not covered by shrubs. This is the aggregate quantity, which is affected by the second multiplier in Equation 8. It involves soil depth (*SOI*), so making the equation take the form of an inverted exponential function where *msh* and *hsr* have *p*1 and *p*2 as their counterparts in Figure 2, respectively. A positive value of *msh* is expected here, meaning that herbs cannot grow unless there is a minimum depth of soil. Thus, regarding this second multiplier, herb production vanishes whenever soil depth is equal to, or lower than, *msh*. The hectare being modelled was assumed not to be a place where livestock is crowded together, for example, around watering points, where herb productivity is also reduced by trampling.

The potential herb production in the whole hectare (*PHP*) is linearly related to annual rainfall (*RNF*), being *phs* the slope and *phi* the *y*-intercept. The latter is taken to have a negative sign (Sullivan and Rohde, 2002, p. 1597):

$$PHP = \max\{0, phs \times RNF - phi\} \tag{9}$$

Soil

To simplify terminology, we consider the soil to be the entire amount of various organic and inorganic materials covering the bedrock, litter included. This is because the purpose of this section of the model is exclusively to represent the annual mass balance over the bedrock, that is, the amounts of material yearly accumulated and removed, whatever its composition may be. Thus, any physical or chemical transformation within the soil is ignored as long as it does not imply a significant variation in mass.

Changes in soil depth (*SOI*) are given by:

$$\mathrm{d}SOI/\mathrm{d}t = BWR + OMR - SER \tag{10}$$

Where: BWR is the bedrock weathering rate, *OMR* is the net rate of deposition of organic matter and *SER* is the net rate of erosion, that is, the imbalance between the rate of erosion and the rate of deposition of soil coming from the upper parts of the slope.

Some authors consider that *BWR* is constant under stable climate and uniform geological conditions (e.g. Biot, 1990). However, it seems that some negative relationship between such a rate and soil depth (*SOI*) must exist, because the thicker the soil, the more the bedrock surface is protected from weathering. The model tentatively includes a negative, linear

[1]Specifically: $sx_t = smoothi(x, d, sx_o) = (\Delta/d)x_{t-\Delta} + (\Delta/d)[1-(\Delta/d)]x_{t-2\Delta} + (\Delta/d)[1-(\Delta/d)]^2 x_{t-3\Delta} + (\Delta/d)[1-(\Delta/d)]^3 x_{t-4\Delta} + \ldots$ *Where: d* is the average adjustment time (small *d* implies quickly decreasing weights and vice versa); sx_o is the initial value of *sx*; Δ is the time-step.

relationship between both variables where *pwr* (the potential weathering rate) and *wsr* (the slope) are parameters:

$$BWR = \max\{0, pwr - wsr \times SOI\} \quad (11)$$

The net rate of deposition of organic matter (*OMR*) is given by:

$$OMR = (GHB + SDR + oma \times SKR) \times (1 - fod) \times mdc \quad (12)$$

Where: GHB is the ungrazed herb biomass (recall Equation 7), which is entirely added to the soil each year because herbs dry out at the end of the growing season and *SDR* is the death rate of shrub biomass (Equation 6). The amount of manure annually deposited by livestock is taken to be proportional to the stocking rate (*SKR*), *oma* being the average waste matter produced per animal. The parameter *fod* (fractional decomposition rate of organic matter) is the fraction of the three previous types of organic materials which is lost in the decomposition process. Finally, *mdc* is a mass-to-depth unit-conversion coefficient.

Erosion had to be related to the two (above ground) biomasses in the model: the ungrazed herb biomass (*GHB*) and the total shrub biomass (*TSB*). However, such a relationship seemed reasonable because these biomasses values refer to the end of the dry season, when vegetation cover is minimal and the highest erosion rates take place.

The equation for the annual net rate of erosion (*SER*) is based on the negative exponential model proposed by Elwell and Stocking (1976) whose general form is $r = b \times \exp\{-\alpha c\}$, where r is the erosion rate, b is the bare soil erosion rate, c is vegetation cover and α is a parameter. In our case, *SER* is a weighted average of the erosion rates happening in the shrub and herb areas, where the weights are the respective cover fractions. The fraction of the hectare not covered by shrub biomass is given by $\max\{0, 1 - scc \times TSB\}$ (recall Equation 8); hence, that covered by herbs is $\min\{1, scc \times TSB\}$. Thus, the equation for *SER* is:

$$\begin{aligned} SER = & \max\{0, 1 - scc \times TSB\} \times BSE \\ & \times \exp\{-ehr \times GHB\} \\ & + \min\{1, scc \times TSB\} \times BSE \\ & \times \exp\{-esr \times TSB\} \end{aligned} \quad (13)$$

Where: BSE is the bare soil erosion rate, and *ehr* and *esr* are parameters (the herb and shrub counterparts of α, respectively). The equation includes biomasses (*GHB* and *TSB*) as proxies for vegetation covers.

The bare soil erosion rate (*BSE*) is an exogenous variable of the model so that its values were normally generated by means of a random variable in simulations. The mean of this variable would depend on the characteristics of the soil and the slope of the modelled hectare, factors which might be considered fixed for a given hectare. The variability of *BSE* over time would be related to the intensity and timing of rainfall. Note, however, that the stochastic behaviour of *BSE* may be thought of as independent of that of the annual rainfall (*RNF*). Indeed, a large amount of rainfall can cause only a little erosion if intensity is low and soil has adequate cover. Conversely, much soil may be lost in a generally dry year if rainfall events, although scarce, are intense enough and soil does not have adequate cover.

Stocking Rate

European rangelands are affected by the Common Agricultural Policy (CAP). This is currently based on the Single Payment Scheme under which grants are decoupled from production and animal numbers (http://ec.europa.eu/agriculture/markets/sfp/index_en.htm). Member States have options on how to calculate and make payments. The model represents the system applied to the Greek communal rangelands. There, a number of subsidized animals, or ‘rights’, were allocated by the Government to every farmer on the base of the number of animals he or she owned in a reference period. Therefore, a total number of rights exist for any village community. This total number divided by the village’s total area of rangelands is the model parameter ‘rights per hectare’ (*rgh*).

Farmers in the Mediterranean rangelands might additionally benefit from the Less Favoured Areas payment scheme (http://ec.europa.eu/agriculture/rurdev/lfa/index_en.htm). However, this grant is much less than the previous one, and only a limited proportion of farmers receive it, because they are required to comply with a range of eligibility criteria.

Nevertheless, because livestock production in any EU communal rangeland is market oriented, stocking rates also depend on the profitability of the livestock grazing business. After all, the 2003 CAP reform sought to allow farmers ‘to adjust production to suit demand /. . ./ in the knowledge that they will receive the same amount of aid’ (quoted from http://ec.europa.eu/agriculture/markets/sfp/index_en.htm).

To reflect this combined situation (free market/subsidies), on the one hand, the model states a linear relationship between the stocking rate (*SKR*) and the expected average gross margin per animal (GMA^e); $gm1$ and $gm2$ are the parameters of such a linear relationship. On the other hand, the stocking rate is not allowed to be less than the number of rights per hectare (*rgh*) whatever the gross margin per animal might be, because it is always worthwhile to obtain subsidies. The latter is assumed to hold even for scenarios of long-lasting unfavourable prices. However, as we will see in a forthcoming section, the model assures that, under such circumstances, no supplementary feed will be supplied to the animals for costs to be kept to a minimum. They will then be fed exclusively with biomass. This was taken to be a likely behaviour for farmers receiving grants which are decoupled from production.

$$SKR = \max\{gm1 \times GMA^{e} + gm2, rgh\} \quad (14)$$

Farmers may follow different strategies for stocking depending on personal circumstances such as risk aversion or opportunity cost (e.g. Quaas *et al*., 2007). However, Equation 14 represents the aggregate response of all the farmers in the communal rangeland. Thus, the equation is simply stating that, in theory, the greater the expected gross margin per animal, the greater the stocking rate. Nonetheless, no *a priori* assumption is made regarding the parameters. Thus, *gm*1 could be very low or even zero in particular cases, meaning that the stocking rate hardly varies or is constant, respectively. In any case, at least *gm*2 would be inversely related to the average opportunity cost of farmers. Indeed, the lesser the average alternative rent outside livestock production, that is, the higher *gm*2, the larger the number of farmers staying in business and thereby the stocking rate for any given value of the expected gross margin per animal. It might be thought that Equation 14 allows the stocking rate to grow limitlessly, but this cannot be the case because it is related to the average gross margin per animal by negative feedback loops.

Specifically, the actual (not the expected) average gross margin per animal (*GMA*) is given by:

$$GMA = PRM \times MYA + (sbh/SKR) + ika - PRS \times SFA - oca \quad (15)$$

Where: PRM is the price of milk, *MYA* is the milk yield per animal, *sbh* are the total subsidies to the hectare, *SKR* is the stocking rate, *ika* is the income from the sale of kids, *PRS* is the price of supplemental feed, *SFA* is the supplementary feed consumed per animal and *oca* are other costs per head. Farmers are assumed to be price takers so that the price of milk (*PRM*) and the price of supplemental feed (*PRS*) are determined by markets and not influenced by regional production and demand. Hence, both prices are exogenous variables of the model. However, *sbh*, *ika* and *oca* were considered to be parameters for the sake of simplicity.

Equation 15 explains the negative feedback existing between the average gross margin per animal (*GMA*) and the stocking rate (*SKR*). On the one hand, the per-head share of a given amount of total subsidies to the hectare (*sbh*) decreases as the stocking rate increases, because any additional animal over the number of rights (*rgh*) is not subsidized. On the other, the biomass available per head decreases as the stocking rate increases, thereby raising the supplementary feed supplied per animal (*SFA*), on average, and thus its cost for a given price (*PRS*). Hence, the stocking rate given by Equation 14 will not grow limitlessly and profitably.

In the model, the stocking rate (*SKR*) is not related to the actual average gross margin per animal (*GMA*) but to its expected value (GMA^{e}) (recall Equation 14). The forming of expectations about *GMA* is formalized by exponential smoothing, where gma_{t} is the average adjustment time and gma_{i} is the initial value of GMA^{e} (recall footnote 1):

$$GMA^{e} = smoothi\{GMA, gma_{t}, gma_{i}\} \quad (16)$$

Consequently, the expected gross margin per animal is a weighted moving average of past figures of the actual one where weights decrease exponentially as they go back over time. This is just an alternative way to formalize the model of adaptive expectations, which is well known in economics (e.g. Sterman, 2000, pp. 428–432). Thus, it is assumed that the impact on the stocking rate of any occasional shift in the actual gross margin per animal is distributed over several years. In other words, it is assumed that the aggregate response of the farmers in the rangeland does not reflect a highly 'opportunistic' (Higgins *et al*., 2007) or 'perfectly reactive' (Anderies *et al*., 2002) strategy. If this were the case, the rangeland would become significantly destocked or restocked every time the actual gross margin per animal significantly changed, even from one year to the next. However, this does not seem to be the case in the European rangelands.

The average adjustment time (gma_{t}) in Equation 16 would be positively related to the ratio of conservative to opportunistic farmers in the communal rangeland. The larger the former group, the slower the aggregate response to changes will be, that is, the higher gma_{t}, because conservative farmers are more reluctant to change their expectations about profits and thus the size of their flocks.

Returning to Equation 14, note that whenever the first argument of the max function is the largest, that is, when $SKR = gm1 \times GMA^{e} + gm2$, the stocking rate will depend on biomass production. In effect, if dry years were simulated, the amount of supplementary feed (*SFA*) would rise (see the Supplementary feed section), and thus the average gross margin per animal (*GMA*) would drop, other things being equal. If the simulated drought persisted, the expectations about the gross margin (GMA^{e}) would lower as well and thus the stocking rate. However, whenever the second part of Equation 14 is the largest, that is, when $SKR = rgh$, the stocking rate is decoupled from biomass production.

The milk yield per animal (*MYA*) is related to the individual intake of energy (*IEA*) by means of an inverted exponential function:

$$MYA = pmy \times (1 - \exp\{-mer \times IEA\}) \quad (17)$$

Thus, *MYA* grows with the intake of energy, showing diminishing marginal returns, until the potential or saturation value (*pmy*) is reached. Comparing this equation with its counterpart in Figure 2, we see that $p1 = 0$ and $p2 = 1/mer$ in this particular case. Both *pmy* and the shape-parameter *mer* would depend on the particular breed.

Animal Consumption of Biomass

The amount of biomass normally required by one animal (*RBA*) is given by:

$$RBA = pbi - bss \times SFA_t \quad (18)$$

Where: pbi is the potential biomass intake per head, SFA_t is the target amount of supplementary feed supplied per animal and *bss* is a parameter. The equation allows different biomass/supplement substitution effects to be considered.

Total available new biomass (*ABP*), meaning that produced within the current year which is edible or accessible to animals, is:

$$ABP = pen \times ASP + peh \times AHP \quad (19)$$

Where: pen is the edible/accessible fraction of the new browse (*ASP*, Equation 2) and *peh* is the edible/accessible fraction of the herb production (*AHP*, Equation 8). Taking both fractions as parameters implies the assumption that unpalatable species are negligible and that accessibility remains unchanged over time. This might seem oversimplifications, but otherwise the model would become considerably more complicated.

The total amount of new biomass consumed per animal (*NBA*) is given by:

$$NBA = \min\{RBA, ABP/SKR\} \quad (20)$$

Where: RBA is the required amount of biomass per animal, *ABP* is the total available new biomass and *SKR* is the stocking rate. The equation simply states that all the biomass that an animal requires will be new biomass unless this is insufficient in the hectare.

The amount of herb biomass consumed by an animal (*HBA*) is a fraction of the total new biomass it consumes (*NBA*):

$$HBA = HPA \times NBA \quad (21)$$

The remainder is the new browse consumed per animal (*NSA*):

$$NSA = (1 - HPA) \times NBA \quad (22)$$

HPA, that is the herb fraction of the total new biomass consumed per animal, is given by:

$$HPA = peh \times AHP/ABP \quad (23)$$

Where: peh is the edible/accessible fraction of the herb production (*AHP*) and *ABP* is the total available new biomass. This equation states that the herb fraction of the total new biomass consumed per animal equals the herb fraction of the available new biomass in the hectare. This implies assuming that the ratio of sheep to goats, that is, grazers to browsers, can vary within the hectare from one year to the next. For example, if there were only shrubs in the hectare, no sheep would enter. This seems likely because different flocks graze a given hectare in a communal rangeland and shepherds decide where to lead which animals by observing pasture composition.

In a year of scarcity, the new biomass that an animal actually consumes (*NBA*) may be less than the biomass it requires (*RBA*) (recall Equation 20). If this is the case, the model states that an average amount of old shrub biomass, equal to the difference *RBA* − *NBA*, is consumed per animal, unless the total edible/accessible old shrub biomass in the hectare is insufficient. Thus, the equation for the old shrub biomass consumed per animal on average (*OSA*) is:

$$OSA = \min\{RBA - NBA, pes \times (TSB - ASP)/SKR\} \quad (24)$$

The second argument of the min function represents the share of old shrub biomass available per animal in the hectare. In effect, *TSB* is the total shrub biomass, *ASP* is the new shrub biomass, *pes* is the edible/accessible fraction of the total old shrub biomass (*TSB* − *ASP*) and *SKR* is the stocking rate. The equation expresses the average consumption per head. In fact, goats are the only animals consuming old shrub biomass.

The total shrub biomass removed by livestock (*SCR*, recall Equation 1) is:

$$SCR = (NSA + OSA) \times SKR \quad (25)$$

Where: NSA and *OSA* are the amounts of new browse and old shrub biomass consumed per animal, respectively, and *SKR* is the stocking rate. In turn, the total herb biomass consumed by livestock (*HCR*, recall Equation 7) is:

$$HCR = HBA \times SKR \quad (26)$$

Where: HBA is the herb biomass consumed per animal and *SKR* is the stocking rate.

Supplementary Feed

In the model, supplementary feed completes the energy intake needed for every animal to achieve production goals. Livestock are assumed to have water at their disposal at any time. The total amount of supplementary feed yearly consumed per head (*SFA*) could be made up of a normal target share (SFA_t) and an occasional extra share (SFA_x), the latter only being supplied in years of biomass scarcity:

$$SFA = SFA_t + SFA_x \quad (27)$$

The target share (SFA_t) is defined as the amount of supplementary feed needed for one animal to reach the target intake of energy (*IEA*) in a normal year where the new biomass is enough for the animals to meet their requirements of biomass, that is, when *NBA* = *RBA* (see Equation

20). The mathematical calculations leading to the equation for SFA_t are given in a footnote[2]. The result is:

$$SFA_t = (IEA - pbi \times BEC)/(sfe - bss \times BEC) \quad (28)$$

Where: IEA is the target intake of energy per animal, *pbi* is the potential biomass intake per animal (Equation 18), *BEC* is the average energy content per unit of new biomass consumed, *sfe* is the energy content per unit of supplementary feed and *bss* is the biomass/supplement substitution coefficient (Equation 18). *BEC* is given by:

$$BEC = hec \times HPA + sec \times (1 - HPA) \quad (29)$$

Where: hec and *sec* are the energy contents per unit of herb biomass and new browse, respectively, and *HPA* is the herb fraction of the total new biomass consumed by one animal (Equation 23).

Model equations allow the calculation of the expression of the economically optimum energy intake per animal (IEA_o) for a year without biomass scarcity. This requires: (i) substituting the expressions for the milk yield per animal (*MYA*, Equation 17) and for the target amount of supplementary feed per animal (SFA_t, Equation 28) into the equation for the gross margin per animal (*GMA*, Equation 15), thereby making *GMA* a function of the per animal intake of energy (*IEA*), exogenous variables and parameters; (ii) working out the expression for the first-order necessary condition for a maximum, that is, d*GMA*/d*IEA* = 0; and (iii) solving this equation for the intake of energy (*IEA*). The result is the first argument of the following max function:

$$IEA_o = \max\{\ln\{[(sfe - bss \times BEC) \times PRM \times pmy \times mer]/PRSt\}/mer, pbi \times BEC\} \quad (30)$$

The max function simply states that the optimum intake of energy per animal (IEA_o) can never be less than the energy provided to each animal by the biomass, because this is a free resource. Such minimum energy is $pbi \times BEC$, where *pbi* is the potential biomass intake per head (recall Equation 18 and note that no supplemental feed would be supplied at the minimum we are considering) and *BEC* is the average energy content of the biomass consumed by one animal.

The first argument of the max function in Equation 30 is not easy to grasp intuitively, so it is not worth recalling what every term means (all of them have already been defined). Note however that through this first argument, the optimum intake of energy (IEA_o) verifies some expected relationships: (i) it is positively related to the price of milk (*PRM*) and to the breed's aptitude for milk production, through the parameters *pmy* and *mer* (recall Equation 17); (ii) it is negatively related to the price of supplementary feed (*PRS*) and to the energy content of the biomass (*BEC*). Therefore, in years of very unfavourable prices, the optimum intake of energy will be no more than the energy supplied by the biomass.

Farmers are probably unaware of exactly what the optimal energy intake is for their animals over time. However, it is assumed that they have enough experience to know the relationships mentioned before so that they show a rational (if not optimal) aggregate response to changes in any of the factors affecting IEA_o, namely *PRM*, *PRS*, breed and *BEC*. In other words, it is assumed that the actual energy intake per animal (*IEA*) is somehow related to the optimal one (IEA_o). Different assumptions about farmers' behaviour could be hypothesized to formalize such a relationship. However, profit maximization seems by itself an appealing assumption because, being grounded on the economic theory, it is not affected by what or how long the scenarios of simulation may be. Thus, it was opted for the model to state the existence of a simple fractional error (*sbo*) between the actual and optimal energy intakes:

$$IEA = (1 + sbo) \times IEA_o \quad (31)$$

In any year with biomass scarcity, where the total new biomass is insufficient to meet the biomass requirements of the animals, that is, where *NBA* equals *ABP*/*SKR* thereby being less than *RBA* (recall Equation 20), the target amount of supplementary feed per head (SFA_t) is no longer able to reach the target amount of energy (*IEA*)[3]. In such years, it is assumed that each animal is supplied with the additional amount of supplemental feed (SFA_x) needed to achieve *IEA*:

$$SFA_x = \max\{0, (IEA - sfe \times SFA_t - hec \times HBA - sec \times NSAt)/sfe\} \quad (32)$$

Where: IEA is the target energy intake per animal, SFA_t is the target amount of supplementary feed per animal, *HBA* is the herb biomass consumed per animal, *NSA* is the new browse consumed per animal and *sfe*, *hec* and *sec* are the energy contents per unit of supplementary feed, herb biomass and new browse, respectively.

It must be said, as a final detail, that in years of biomass shortage, the first argument of the max function in Equation 30 no longer expresses the optimum intake of energy.[4]

[2]It follows that: IEA = sfe × SFA_t + hec × HBA + sec × NSA = sfe × SFA_t + (pbi − bss × SFA_t) × [hec × HPA + sec × (1 − HPA)] = sfe × SFA_t + (pbi − bss × SFA_t) × BEC. Hence, Equation 28. See variable and parameter definitions in the text. Equations 18, 21 and 22 and also the assumption that *NBA* = *RBA* have been taken into account in the calculations.

[3]Assuming that the old shrub biomass has a negligible energy content, it may be checked that for one animal to intake the target amount of energy (*IEA*) when *NBA* = *ABP*/*SKR*, the amount of supplemental feed should be SFA_t = [*IEA* − (*ABP*/*SKR*) *BEC*]/*sfe*, an amount which is greater than that of Equation 28.

[4]It may be checked that the first argument in Equation 30 should be ln {*sfe PRM pmy mer*/*PRS*}/*mer* when *NBA* = *ABP*/*SKR*.

Therefore, the fractional error between the actual and optimal energy intake will be different from *sbo* in such special years.

MODEL CALIBRATION FOR ASKOS IN LAGADAS (GREECE)

Lagadas County is located NE of Thessaloniki, in northern Greece, and has an area of about 200 000 ha. The elevation ranges from 35 to 1100 m asl. The climate is semi-arid Mediterranean with cold winters. The geology is dominated by metamorphic rocks, which result in acidic soils, and the topography is gentle to steep. Soils contain 57 per cent sand, 21 per cent silt and 22 per cent clay (Zarovali, 2009), indicating a sandy loam texture. There are a variety of land-use types with rangelands covering about 40 per cent of the area. They are dominated by kermes oak (*Quercus coccifera* L.) shrublands with crown densities ranging from very open (<15 per cent shrub cover) to very dense (>70 per cent shrub cover). In the clearings, grasslands or rainfed agricultural areas are found, mainly used for cereal production. Therefore, the Lagadas rangelands provide two types of forage, herbs (herbaceous species) and browse (shrubs).

Rangelands are state-owned areas communally grazed by livestock. In the year 2000, there were about 150 000 goats and 106 000 sheep in the county (National Statistical Service of Greece, www.statistics.gr). Goats and sheep are both dual-purpose animals, chiefly raised for milk and secondarily for meat (kids or lambs). Rangelands, especially shrublands, are grazed mainly by goats because they can feed on both herbaceous and shrub species. Grazing is carried out the whole year round, but mostly in the winter, spring and autumn. During summer, goats usually graze on cereal stubble on the land belonging to the village or, very occasionally, move to rangelands in other areas located at higher elevations. In late winter to early spring, private arable fields sown with cereals (artificial pastures) are also used for grazing (Yiakoulaki *et al*., 2005). In addition, animals are also fed with hay and compound feed during periods of feed shortage, especially in the winter (Yiakoulaki *et al*., 2005). Sheep, on the contrary, graze less on rangelands. They mainly feed on artificial pastures and cereal stubble and use grasslands or large clearings among shrubs in spring and autumn. In addition, they are fed with hay and compound feed almost all 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 €7 870 590 and €8 918 100, respectively. Almost 40 per cent of this income corresponded to subsidies that farmers received from the EU. Without these subsidies, the profit of farmers per goat or sheep would have been very low or even negative (Kitsopanidis *et al*., 2009).

Model calibration focused on Askos, a typical village in Lagadas County with 4000 ha of rangelands. In 2005, the number of goats and sheep amounted to about 7200 and 2000 heads, respectively. Data availability for this case study was irregular. There were samples of data on the exogenous variables. However, for most of the endogenous variables and parameters, there were only sparse data coming from research databases, the literature and expert opinion. Finally, no quantitative information was available for one set of parameters. Tables I and II show the initially available values of endogenous variables and parameters, respectively.

Exclusively for calibration purposes, the four exogenous variables of the model were treated as parameters by taking their respective mean values. The means of annual rainfall (*RNF*), price of milk (*PRM*) and price of supplemental feed (*PRS*), consisting of barley, wheat, maize and cotton, were estimated from samples of annual data ($n = 72$, 22 and 46 years, respectively). The mean of the bare soil erosion rate (*BSE*) was estimated by taking into account the parent rock and soil type at the Lagadas site (D. Alifragis, pers. comm.). These four values are shown in Table III.

All of the available values for the variables and parameters of the model (the means of the exogenous variables included) were assumed to be part of a benchmark, which would happen in a single, unspecified year. Therefore, calibration consisted of finding values for the unknown parameters to complete such a benchmark state coherently. In other words, different values within plausible ranges were probed for each unknown parameter until obtaining a set of figures best fitting into the benchmark state as a whole. Often, the values were first probed with isolated sections of the model. Apart from that, several data referred to other states of the system were additionally required to calibrate some parameters; these data are also included in Table I.

Calibrated parameters are shown in Table II. Only one issue about them is stressed here: The fractional error (*sbo*) between the actual intake of energy per animal and the optimal one was 0·336, meaning that farmers are over-supplementing in Lagadas. Therefore, they would improve their gross margins by reducing supplementary feed. This result was also reported by Kitsopanidis *et al*. (2009).

As already mentioned, stochastic values, sampled from appropriate random variables for each simulated year, were assigned to the exogenous variables for time-running simulations of the model. For convenience, independent, normal random variables were used, whose means and standard deviations are shown in Table III. The standard deviations of annual rainfall (*RNF*), price of milk (*PRM*) and price of supplementary feed (*PRS*) were estimated from their corresponding samples. To estimate the standard deviation of the bare soil erosion rate (*BSE*), a sample of erosion rates in Askos ($n = 16$) was taken from the PESERA database (Kirkby *et al*., 2004). First, the frequency distribution of these erosion rates was calculated. Then, many time-running simulations of the model were performed, each with a different value of the standard deviation of *BSE*. The value finally chosen was that

Table I. List of endogenous variables, initially available values and units

Name	Definition	Value	Units
ABP	Available biomass	2472	$kg\,ha^{-1}\,y^{-1}$
AHP	Aboveground herb production	890 (1300)[a]	$kg\,ha^{-1}\,y^{-1}$
ASP	Aboveground shrub production	2200	$kg\,ha^{-1}\,y^{-1}$
BEC	Biomass average energy content	0·358	$FU\,kg^{-1}$
BWR	Bedrock weathering rate	0·26	$mm\,y^{-1}$
GHB	Ungrazed aboveground herb biomass	623	$kg\,ha^{-1}\,y^{-1}$
GMA	Gross margin per animal	334	$€\,AU^{-1}\,y^{-1}$
GMA^e	Estimated gross margin per animal	—	$€\,AU^{-1}\,y^{-1}$
HCR	Herb biomass consumption rate	266·96	$kg\,ha^{-1}\,y^{-1}$
HBA	Herb biomass consumed per animal	470	$kg\,AU^{-1}\,y^{-1}$
HPA	Herb proportion in biomass consumed per animal	0·29	dmnl
IEA	Intake of energy per animal	2529	$FU\,AU^{-1}\,y^{-1}$
IEA_o	Optimum intake of energy per animal	—	$FU\,AU^{-1}\,y^{-1}$
MYA	Milk yield per animal	954	$kg\,AU^{-1}\,y^{-1}$
NBA	New biomass consumed per animal	1633	$kg\,AU^{-1}\,y^{-1}$
NSA	New shrub biomass consumed per animal	1163	$kg\,AU^{-1}\,y^{-1}$
OMR	Organic matter deposition rate	—	$mm\,y^{-1}$
OSA	Old shrub biomass consumed per animal	—	$kg\,AU^{-1}\,y^{-1}$
PHP	Potential herb production for a given soil depth	1900	$kg\,ha^{-1}\,y^{-1}$
PSP	Potential aboveground shrub production	2200	$kg\,ha^{-1}\,y^{-1}$
RBA	Required biomass per animal	1633	$kg\,AU^{-1}\,y^{-1}$
SFA	Supplemental feed consumed per animal	2181	$kg\,AU^{-1}\,y^{-1}$
SFA_t	Target supplemental feed consumed per animal	2181	$kg\,AU^{-1}\,y^{-1}$
SFA_x	Extra supplemental feed consumed per animal	—	$kg\,AU^{-1}\,y^{-1}$
SCR	Shrub biomass consumption rate	660·58	$kg\,ha^{-1}\,y^{-1}$
SDR	Shrub biomass death rate	—	$kg\,ha^{-1}\,y^{-1}$
SER	Soil erosion net rate	0·3	$mm\,y^{-1}$
SKR	Stocking rate	0·568	$AU\,ha^{-1}$
SOI	Soil depth	450 (750)[b]	mm
SSM	Subsoil moisture	67 (84)[a]	mm
TSB	Total aboveground shrub biomass	11 000	$kg\,ha^{-1}$
XSP	Maximum potential aboveground shrub production	3020 (4200)[a]	$kg\,ha^{-1}\,y^{-1}$

[a]Value for *RNF* = 600.
[b]Value for *BWR* = 0.

making the frequency distribution of the simulated erosion rates (*SER*) best fit the recorded one.

When the model was entirely calibrated, its behaviour was reviewed by experts who knew the site well. Different scenarios were analysed in order to assure that simulations were in agreement with their opinion.

As an illustration, Figure 3 shows the time trajectories of the main endogenous variables obtained by running the model over 150 years. Note that, with the exception of the soil, the variables wave around their respective benchmark values (Table I), as expected after the calibration process followed. Nearly 10 mm of soil was lost during the simulated period, showing that some degradation through erosion is happening in Lagadas. However, for the soil to entirely disappear, and thus the system to collapse, the simulation of the model had to be lengthened until the year 3700. This is not a figure to be taken literally by any sensible reader for many good reasons, for example, the parameters of the model will not remain constant over such a long period. Nevertheless, it seems to indicate that erosion would not presently be the main cause for concern in Lagadas. More is said on the matter in the next section.

RANKING POSSIBLE DRIVERS OF DEGRADATION IN LAGADAS

Which parameters, if they change from their benchmark values, would most likely hasten degradation in Lagadas? To give an answer to this question, a Plackett–Burman sensitivity analysis (PBSA) was carried out. A detailed description of the procedure is given by Beres and Hawkins (2001) so it is not repeated here. Essentially, it is a statistically sound method, which measures the effects of each parameter on target output variables in an efficient way in terms of the number of scenarios needed. First, upper and lower values must be assigned to each parameter. Then, these values are specifically sampled to form each scenario in the procedure. An important feature is that the effects of a parameter are not measured under the all-other-things-being-equal assumption, but are averaged over variations made in all other parameters.

Table II. List of parameters, initially available and calibrated values and units

Name	Definition	Value	Units
bss	Biomass–supplement substitution coefficient	0·38[a]	dmnl
ehr	Erosion–herb biomass relation parameter	0·003[a]	ha year kg^{-1}
esr	Erosion–shrub biomass relation parameter	0·00014[a]	ha kg^{-1}
fod	Fractional organic matter decomposition rate	0·85	dmnl
fsd	Fractional shrub biomass death rate	0·14[a]	y^{-1}
*gm*1	Slope of the linear equation in *SKR* and *GMA*[e]	588·57[a]	AU^2 year €$^{-1}$ ha^{-1}
*gm*2	*SKR*-intercept	0[a]	AU ha^{-1}
gma_i	Gross margin per animal, initial value	334	€ AU^{-1} y^{-1}
gma_t	Gross margin per animal, adjustment time	5[a]	year
hec	Herb energy content	0·5	FU kg^{-1}
hsr	Herb–soil relation parameter	60[b]	mm
ika	Income from the selling of kids per animal	375	€ AU^{-1} y^{-1}
mdc	Mass-to-depth unit-conversion coefficient for organic matter	0·000057	mm ha kg^{-1}
mer	Milk–energy intake relation parameter	0·00036[a]	AU year FU^{-1}
mrr	Moisture–rainfall relation parameter	0·14	year
msh	Minimum soil depth for herb production	220	mm
oca	Other cost per animal (not supplemental feed)	590	€ AU^{-1} y^{-1}
oma	Organic matter per animal	1501	kg AU^{-1} y^{-1}
pbi	Biomass intake per animal without supplemental feed	2462	kg AU^{-1} y^{-1}
peh	Proportion of available herb production	0·8	dmnl
pen	Proportion of available shrub production	0·8	dmnl
pes	Proportion of available old shrub biomass	0·6	dmnl
phi	*PHP*-intercept	1791·4[a]	kg ha^{-1} y^{-1}
phs	Slope of the linear equation in *PHP* and *RNF*	7·61[a]	kg ha^{-1} mm^{-1}
pmy	Potential milk yield per animal	1600[a]	kg AU^{-1} y^{-1}
pwr	Potential bedrock weathering rate	0·65[a]	mm y^{-1}
rgh	Subsidized animals (rights) in the hectare	0·39	AU ha^{-1}
rnf_i	Rainfall, initial value	485	mm y^{-1}
rnf_t	Rainfall, adjustment time	3[b]	year
sbh	Total subsidies to the hectare	136	€ ha^{-1} y^{-1}
sbo	Percent error between *IEA* and IEA_o	0·336	dmnl
scc	Shrub biomass to cover percentage conversion coefficient	0·000048	dmnl kg^{-1} ha^{-1}
sec	Shrub energy content	0·3	FU kg^{-1}
sfe	Supplemental feed energy content	0·892	FU kg^{-1}
spt	Slope of the linear equation in *PSP* and *TSB*	0·0746[a]	y^{-1}
*ss*1	Shrub–soil relation parameter 1	0	mm
*ss*2	Shrub–soil relation parameter 2	100[b]	mm
sxs	Slope of the linear equation in the *XSP* and *SSM*	69·41[a]	kg ha^{-1} y^{-1} mm^{-1}
wsr	Weathering–soil depth relation parameter	0·00087[a]	y^{-1}
xsi	*XSP*-intercept	1630·6[a]	kg ha^{-1} y^{-1}

[a]Calibrated parameter.
[b]Tentative figure.

In our case, upper and lower values were assigned to parameters by increasing/decreasing the corresponding benchmark values by 10 per cent. An exception was made for the shrub–soil relationship parameter (*ss*1), whose benchmark value is zero (Table II), so 10 and −10 mm were arbitrarily taken as its upper and lower values, respectively. Ninety-six different scenarios were specified by adequately sampling from the upper and lower values.

In order to assess how changes in the variability of the exogenous variables affect the system, the standard deviations of such variables were included within the set of parameters analysed. This means that every simulation in the procedure was run stochastically. Therefore, in order to achieve a robust analysis, 100 simulations were run under each scenario, each one with a different random seed. Hence, a total of 9600 simulations were used in the analysis. The time horizon for the PBSA was set at 100 years. The target variables were the means of soil depth (*SOI*) and above ground shrub biomass (*TSB*) over the 100 values recorded (at year 100) under each scenario. Table IV shows the 20 parameters with the highest impacts on *SOI* and *TSB*. The sign of the figures indicates the direction of the corresponding effect.

Note that the mean annual rainfall (*rnf_mean*) had the strongest impact on both soil and shrubs. A reduction in average rainfall would therefore be the main cause of degradation through erosion in Lagadas. Conversely, an

Table III. List of exogenous variables, means, standard deviations and units

Name	Definition	Mean	*SD*	Units
BSE	Bare soil erosion rate	1·6	1	$mm\,y^{-1}$
PRM	Price of milk	0·65	0·105	€ kg^{-1}
PRS	Price of supplemental feed	0·143	0·006	€ kg^{-1}
RNF	Rainfall	485	112	$mm\,y^{-1}$

increase in average rainfall would be the principal driver of shrub invasion.

Other parameters significantly affecting soil depth were those of the linear equation determining the bedrock weathering rate (*pwr* and *wsr*, Equation 11), those of the linear relationship between rainfall and herb production (*phs* and *phi*, Equation 9) and two of those involved in the relationship between shrub production and rainfall (*mrr* and *sxs*, Equations 4 and 5). Interestingly, only three factors related to the stocking rate were included among the 20 most strongly affecting the soil: the potential biomass intake per animal (*pbi*), other costs per animal different from supplementary feed (*oca*) and the mean price of supplementary feed (*prs_mean*). In any case, their impact was very low or negligible (Table IV). This indicates that degradation through erosion in our case study is barely sensitive to variations in livestock numbers. Consequently, a strong reduction of the stocking rate would be needed if it were planned to avoid the loss of soil shown in Figure 3 by cutting animal numbers. Indeed, a simulation specifically carried out to explore this issue showed that the subsidies to the hectare (*sbh*) should be reduced by 60 per cent, all other things being equal, to achieve a stocking rate that would render no soil erosion. This means that the stocking rate should fall by around 26 per cent, that is, reaching values never observed in the area, and the gross margin per animal would fall by around 30 per cent. Taken together, both figures would make farmers' earnings drop by more than half (52 per cent).

The PBSA showed that shrub biomass in Lagadas would be much more sensitive than soil to exogenous influences (Table IV). Again, three parameters involved in the relationship between rainfall and shrub productivity (*mrr*, *sxs*, *xsi*, Equations 4 and 5) were among the most important ones

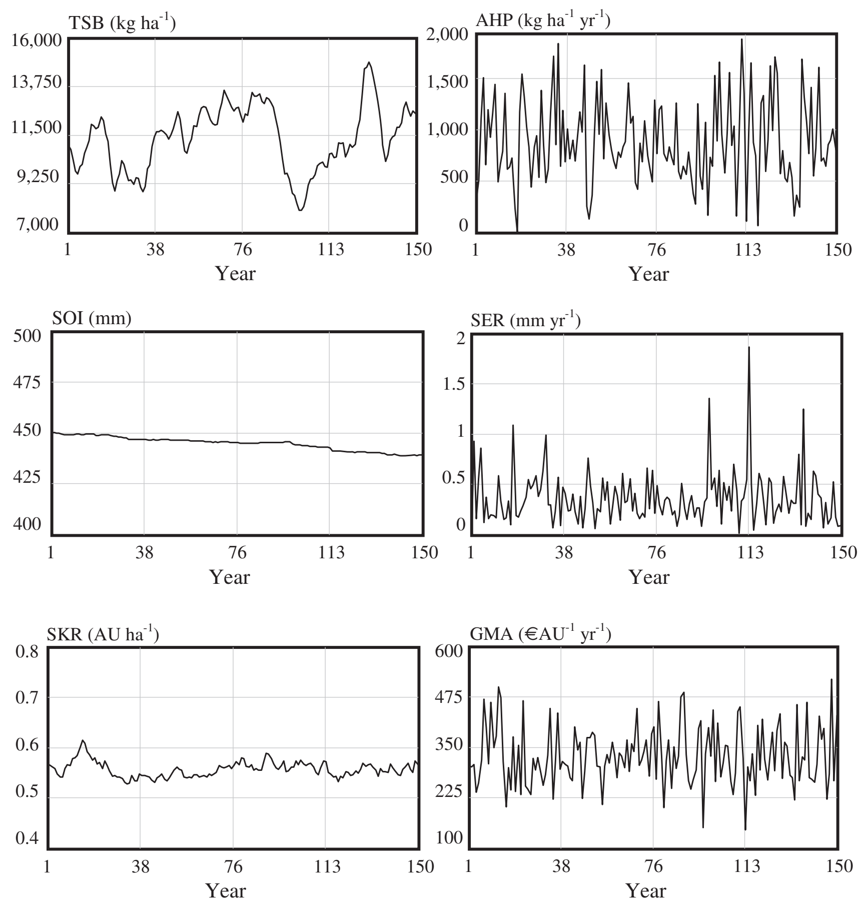

Figure 3. Simulated time trajectories of total shrub biomass (*TSB*), annual herb production (*AHP*), soil depth (*SOI*), erosion rate (*SER*), stocking rate (*SKR*) and gross margin per animal (*GMA*).

Table IV. The greatest impacts on soil depth (*SOI*) and total shrub biomass (*TSB*)

Parameter	Effects on soil (%)	Parameter	Effects on *TSB* (%)
rnf_mean	4·25	*rnf_mean*	38·10
pwr	2·70	*mrr*	36·07
phs	2·57	*sxs*	35·41
wsr	−1·70	*xsi*	−12·71
phi	−1·62	*fsd*	−12·53
mrr	1·47	*pbi*	−11·53
sxs	1·37	*spt*	−6·52
pbi	−1·34	*oca*	5·50
bse_mean	−1·25	*prs_mean*	−4·41
esr	1·00	*ika*	−3·72
ehr	0·72	*gm*1	−3·64
hpr	0·71	*bss*	3·18
scc	−0·68	*phs*	2·73
fod	−0·64	*sbh*	−2·62
peh	−0·63	*sec*	−1·89
oca	0·62	*hpr*	−1·82
xsi	−0·6	*sfe*	1·71
bse_std	−0·57	*phi*	−1·65
pen	0·54	*hec*	−1·61
prs_mean	−0·42	*scc*	−1·46

Namely, a 10% increase in parameter *x* produced the corresponding percentage change in target variable *y* (*SOI* or *TSB*) at year 100.

affecting shrub biomass. However, the remarkable finding was that many parameters related to livestock appeared in the list, namely the potential biomass intake per animal (*pbi*), other costs per animal different from supplementary feed (*oca*), the mean price of supplementary feed (*prs_mean*), the income from the sale of kids (*ika*), the slope of the linear equation between the stocking rate and the expected gross margin per animal (*gm*1), the biomass/supplement substitution coefficient (*bss*), the subsidies to the hectare (*sbh*) and the energy content per unit of supplementary feed (*sfe*).

oca, *ika* and *sbh* exclusively appear in the equation for the gross margin per animal (Equation 15) and through this variable affect the stocking rate. Their impacts showed expected signs in the PBSA: *ika* and *sbh*, which are positively related to the stocking rate, showed negative signs meaning that shrub biomass decrease when they increase, and *oca*, which is negatively related to the stocking rate, showed a positive sign. *gm*1 is exclusively used in the equation for the stocking rate (Equation 14). By increasing this parameter, the model yields higher stocking rates for given values of the expected gross margin. As a result, the negative impact on shrub biomass that *gm*1 showed in the PBSA is not unexpected. Although *pbi* may occasionally determine the optimal energy intake (Equation 30), it is mainly positively related to the actual biomass consumption by livestock (Equation 18). This explains its negative impact on shrub biomass. Similarly, although *bss* is one of the many factors involved in determining the energy intake per animal (Equation 30), it is clearly negatively related to the biomass an animal consumes for a given amount of supplementary feed (the substitution effect in Equation 18). Hence, *bss* showed a positive impact on shrub biomass. Regarding *prs_mean*, on the one hand, it is negatively related to the gross margin and thus the stocking rate; but the latter has the number of rights as a minimum value. On the other, if *prs_mean* is high, farmers demand less supplemental feed, thereby increasing the proportion of biomass consumed by animals. This explains then the negative sign that *prs_mean* showed in the PBSA. The remaining parameter, *sfe*, is involved in relationships with opposite effects. Indeed, if *sfe* increases, then less amount of supplementary feed is needed to achieve a given level of energy intake (Equations 28 and 32) so that its substitution effect is less and the animals consume more biomass. However, increasing *sfe* also implies increasing the energy intake (Equation 30) and thus supplementary feeding. The latter was the effect prevailing after averaging for the 9600 simulations performed, because *sfe* showed a positive impact on shrub biomass in the PBSA. Nevertheless, this impact was low.

In conclusion, the PBSA showed that many parameters that are positively related to either the stocking rate or the biomass consumed per animal play, to a greater or lesser extent, their expected role on controlling shrub biomass. Thus, to sum up, livestock, in general, and factors increasing farmers' profits, in particular, would currently be helping to combat shrub invasion in Lagadas while having low impacts on erosion rates.

DISCUSSION ON THE METHODOLOGY

Any particular result or assessment presented so far must be deemed tentative because data were not enough to ensure statistical soundness. Nonetheless, they are our best conditional estimations, that is, given the knowledge and data available for the time being. The hypotheses and assumptions stated in the model should be regarded as tentative, too, because empirical evidence did not allow them to be statistically tested either. However, they definitely express our current understanding of the different parts of the system.

Insufficient as it may be, quantitative information in Lagadas is abundant compared with that on rangelands in other parts of the world. Despite this, it was necessary to make some simplifying assumptions in order to keep the number of parameters requiring calibration to a minimum, as was indicated throughout the model description. Data insufficiency on many socio-ecological systems is an undeniable fact which presumably will not be solved in the short term. Thus, the dilemma exists on whether it is worth developing applied models. Obviously, the authors are convinced that it is and hope that this work will help encourage readers to think alike.

In an attempt to compensate somewhat for the lack of sufficient quantitative information, we tried to give to the model a high degree of internal coherence, thereby making it more reliable. To achieve such coherence, we sought to represent both the main feedbacks acting within the system and the limits every variable could not surpass even under extreme conditions, so following the recommendations of some authors, for example, Sterman (2000) and Hahn *et al*. (2005).

Avoiding the all-other-things-being-equal 'way of thinking' (Saltelli and Annoni, 2010) at the time of assessing the drivers of degradation was deemed important, too. For example, the result of the PBSA showing that mean rainfall is the most important factor affecting both soil loss (if decreased) and shrub invasion (if increased) in Lagadas could be thought of as implying that other rangelands with a lower mean rainfall are more threatened by erosion and less by shrub invasion. However, this is not necessarily the case. In a different site, not only the mean annual rainfall changes but most of the parameters, if not all, change, too. This overall shift in the parameter space may cause the impacts of any of them (say mean rainfall) to rank differently to Lagadas. Hence, the assessments here presented cannot be extrapolated. Going further, any given system constantly shifts in the parameter space over time because most of its parameters actually vary over time. Therefore, the ranking of parameters (and other dynamic features as well, such as regions of attraction and equilibria) might be changing even from one year to the next for any given system. This implies that degradation requires being regularly assessed or monitored.

Building models means facing the 'dilemma of representation', which refers to the problematic task of finding an adequate scale for a model (Perry and Millington, 2008). If the model aims at monitoring degradation, it has to endure, so that its maintenance must not be too costly. This is a pragmatic argument in favour of tractable models focused on key processes only. However, the critical processes interacting in socio-ecological systems belong to different fields. Hence, tractability must not stop the model being multidisciplinary. Obtaining an adequate combination of these two features was one of the challenges we faced at the time of building the model presented here, where subjects belonging to rangeland ecology, soil science, economics, agricultural policy, livestock management and dynamic modelling had to be embraced. Hopefully, the scale given to the model will be a contribution to the study of degradation in Mediterranean rangelands.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to Dr Dimitrios Alifragis, forest soil scientist, and Dr Maria Yiakoulaki, range scientist, for providing the raw data and information on soil parameters and animal behaviour, respectively, for the Lagadas study area. Also, we thank the two anonymous reviewers of the paper for their contribution.

This study was funded by the European Union under the Project titled 'DeSurvey: A surveillance system for assessing and monitoring of desertification', EU contract No. IP-003950.

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