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Assessing the sensitivity of a Mediterranean commercial rangeland to droughts under climate change scenarios by means of a multidisciplinary integrated model

J. MARTÍNEZ-VALDERRAMA [a,b*], J. IBÁÑEZ [c], M. A. IBÁÑEZ [c], F. J. ALCALÁ [d,e], M. E. SANJUÁN[b], A. RUIZ[b], G. DEL BARRIO[b]

[a] Instituto Multidisciplinar para el Estudio del Medio 'Ramón Margalef', Universidad de Alicante, Edificio Nuevos Institutos, Ctra. de San Vicente del Raspeig s/n
03690 San Vicente del Raspeig, Alicante, Spain.
[b] Estación Experimental de Zonas Áridas (CSIC), Ctra. Sacramento s/n, La Cañada de San Urbano, 04120 Almeria, Spain
[c] Departamento de Economía Agraria, Estadística y Gestión de Empresas, Universidad Politécnica de Madrid, Madrid 28040, Spain
[d] Instituto Geológico y Minero de España (IGME), Ríos Rosas 23, 28003 Madrid, Spain
[e] Instituto de Ciencias Químicas Aplicadas, Facultad de Ingeniería, Universidad Autónoma de Chile, 7500138 Santiago, Chile

*Corresponding author. Email: jaime.mv@ua.es

Abstract

Rangeland productivity is strongly conditioned by the amount and temporal distribution of precipitation. Thus, the worsening of droughts with climate change could be a serious threat to their existence. This paper presents a modelling study aimed at evaluating the sensitivity of a valuable type of commercial rangelands, namely Spanish dehesas, to increases in the frequency and intensity of droughts driven by climate change.

The assessment consisted in a multi-way ANOVA carried out on the basis of 5,400 simulations of a multidisciplinary integrated model. It included two blocking factors linked to climate change scenarios, namely Representative Concentration Pathway and downscaling method, and two treatment factors, namely return period and severity of droughts. The levels of all factors were included as part of the simulation scenarios. The response variables constituted a summary of model's behaviour throughout one simulation. They were average profits per farmer and average stocking rate, both calculated over the entire simulation period, and remaining soil depth at the end of the simulation.

The effects of the treatment factors on the response variables were small for all blocks, thereby suggesting that the sensitivity, and thus the vulnerability, of Spanish dehesas to the worsening of droughts would be low under climate change. Farmers were defined as conservative in all model simulations, that is, they minimized changes in the size of their herds and bought supplementary feed to meet shortfalls in livestock feed unless it was excessively expensive. Thus, we conclude that this group strategy could explain the adaptive capacity of Spanish dehesas to droughts.

This paper shows that multidisciplinary integrated models are valuable learning tools to acquire insights into the relationships between climate, ecologic and socio-economic factors. Although there is a recurrent call for holistic studies, they are still rare in the rangeland literature. Hopefully, this paper will motivate some researchers to consider this approach.

Keywords:

Rangeland; Drought-enduring strategies; System Dynamics; Climate change; Vulnerability; Supplementary feed; Conservative farmers

1. Introduction

Rangelands are defined as lands where people have intervened to manage natural vegetation with livestock for economic gain (Menke and Bradford, 1992). They provide numerous environmental, social and economic services (Lund, 2007; Sala et al., 2017). Global rangeland area is 29 million km^2, of which 63% is found in drylands (Cherlet et al., 2018). They support 2 billion humans and 50% of global livestock (MEA, 2005) and are essential in developing countries, providing food and income to the majority of the 1.2 billion people living on less than $1 per day (Bedunah and Angerer, 2012).

The increasing frequency and duration of droughts (Asadi Zarch et al., 2015; Cook et al., 2015; Fu and Feng, 2014; Maestre et al., 2016) and the foreseeable aridification of mid-latitudes (Feng and Fu, 2013; Lin et al., 2018; Park et al., 2018), as a consequence of global warming, pose major threats to rangelands. Thus, vulnerability to drought in pastures in semi-arid areas could lead to serious ecological and economic consequences (Brown et al., 2016; Iglesias et al., 2016; Vetter, 2009). The threat is particularly acute for Europe and the Mediterranean, where some studies point out that what is now extreme droughts would become standard weather (Samaniego et al., 2018).

Vulnerability assessment involves addressing two issues: the potential impact of a threat and the capacity of the system to adapt to it (Downing and Bakker, 2000; Keenan and Krannich, 1997). However, to evaluate the former, exposure and sensitivity assessments are required, so vulnerability assessments involve evaluating three terms in total (Brown et al., 2016; Glick et al., 2011; Joyce and Marshall, 2017; Joyce et al., 2013). Definitions of these terms referred to the vulnerability of rangelands to droughts are given by Brown et al. (2016): 'Exposure is the likelihood of an event occurring, i.e. how often and how severe is the drought'; 'Sensitivity defines how a particular organism, community, or system (economic or ecological) will respond to a particular event.'; and 'Adaptive capacity is a measure of how well a particular plant community, ranch, region, or sector can withstand the impacts of a drought based on the ability of individuals and institutions to respond positively.' It follows from these definitions that a rangeland will be highly vulnerable to droughts when its exposure is high, its sensitivity is high and its adaptive capacity is low.

Drought vulnerability assessment is an innovative interdisciplinary field of research encompassing engineering, ecology, hydrology, catastrophe management and sociology (Adger, 2006). Thus, this type of studies meets the challenge of integrating pieces of knowledge and data accumulated in various disciplines into a common framework, and to disclose the logical consequences of this integration when combined with long-term climatic data (Cipriotti et al., 2019; Lohmann et al., 2012; Paruelo et al., 2008). Multidisciplinary integrated models serve this purpose, thus allowing a deeper understanding of the relationships between climatic, ecological and socio-economic factors, and helping policy makers and managers to develop more realistic approaches to climate change (Asner et al., 2004; Bedunah and Angerer, 2012; Iglesias et al., 2016; Jakoby et al., 2014; Joyce et al., 2013; Thornton et al., 2009).

Ibáñez et al. (2020) used such a model to evaluate the sensitivity of key subsystems in commercial rangelands, namely the economic, social, grass and soil subsystems, to a large number of factors and drivers, including two drought-related factors: the frequency and the severity of droughts. They found that the sensitivity of the four subsystems to the last two factors was low in the commercial rangelands for which the model was calibrated, namely Spanish dehesas. Since a high sensitivity is a requisite for a rangeland to be highly vulnerable, as indicated above, a low sensitivity to the worsening of droughts suggests that vulnerability would be low for the mentioned case study. This could be explained by two features of the modelled system: the predominance of conservative farmers, i.e. farmers who are relatively unresponsive to changing economic circumstances, and the use of supplementary feed for dealing with droughts. Hence, the synergy between these two features could provide adaptive capacity to droughts for Spanish dehesas (Section 4).

However, in order to carry out this sensitivity assessment, the authors parameterized the model to reflect a default or historical state of the system, that is, a state where the likely effects of climate change were not considered. Therefore, the following research questions arise: Under the effects of climate change, that is, under more arid climatic conditions, where the need for supplementary feed, and thus production costs, are expected to experience a generalized increase due to reduced grass production, will the current drought management strategy continue to be effective? Will it continue to provide adaptive capacity for the system? Will the sensitivity of Spanish dehesas, and thus their vulnerability, to increases in the frequency and severity of droughts continue to be low?

The aim of the modelling study presented in this paper is to provide answers to these questions. For this purpose, the same multidisciplinary integrated model was utilized, but now it was run under a number of climate change scenarios predicted for the area.

Naturally, our initial hypothesis, based on the previous results, was that the sensitivity and vulnerability in question would remain low.

Dehesas (montados in Portugal) are silvo-pastoral ecosystems covering 90,000 km^2 in the SW of the Iberian Peninsula. Our study is justified by the multifaceted importance of these social-ecological systems. Despite they are not exempt from human-induced threats, they are among the best preserved extensive farming systems in Europe, and are considered to be an exemplary land use which favours biodiversity conservation (Moreno and Pulido, 2009). Besides, dehesas are representative for other Mediterranean rangelands (Pulido and Picardo, 2010).

This paper is structured as follows: Section 2 provides a brief outline of the model and gives details about the procedure followed to assess sensitivities. Results are presented in Section 3 and discussed in Section 4. Finally, the main conclusions drawn from the study are presented in Section 5. A Supplementary Document provides some detailed results of the sensitivity analysis.

2. Material and methods

2.1. System Dynamics modelling

There is a recurrent call in the rangeland literature for an integrated multidisciplinary approach resolving the conflicting points of view of economics and ecology (Berrouet et al., 2018; Costanza, 1996; Engler and von Wehrden, 2018; Herrero and Thornton, 2013; Maestre et al., 2012; Reynolds et al., 2007; Stafford Smith et al., 2007; Vetter, 2005). System Dynamics (SD) modelling (Forrester, 1961) is an ideal tool for that purpose because it advises to take a holistic view of the system under study. SD modelling embodies System Thinking through the implementation of differential equation systems and is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics and engineering (Elsawah et al., 2017; Sterman, 2000).

A SD model is a stock-and-flow structure of first-order differential equations which is commonly used to generate the time trajectories of model variables under different simulation scenarios. The model structure is made up of causal feedback loops, which include nonlinear relationships and delays. This structure constitutes *per se* a holistic factor in the dynamics of the system which is easily overlooked, with the result that the behaviour of these complex models frequently turns out to be counterintuitive (Sterman, 2000).

Strong points of SD may be summarized as follows (Kelly et al., 2013): (i) SD models are useful learning tools that help improve system understanding and foster system thinking skills and knowledge integration for modellers and end users. This is true even for their first stage of development, i.e. as conceptual models. (ii) SD modelling is widely accessible because of the development of high-level software platforms. (iii) SD literature has made rich contributions to approaches informing on the modelling process, including data collection methods, knowledge elicitation/mapping techniques, and policy analysis.

2.2. Model overview

Our multidisciplinary integrated SD model represents a commercial farming area including variable numbers of farmers and livestock. Farms are extensive, privately owned, and produce weaned animals for sale (hereafter, the output). The model also represents the dynamics of the main local markets involved, and includes ecosystem variables such as herbage mass, soil moisture and soil depth.

The climate of the area is characterized by the alternation of dry and wet seasons and the regular occurrence of droughts. Herbage mass only consists of annual species. No woody cover is considered. Therefore, when the model is applied to dehesas –which have a disperse tree cover– it represents just the grasslands surrounding the trees. However, the experts in dehesas that advised during the modelling processes (Ibáñez et al., 2014a) deem that the neglect of trees is not a serious drawback of the model because it represents the rest of subsystems satisfactorily.

The model results from the integration and upgrading of earlier versions (Ibáñez et al., 2014a, 2014b, 2016, 2020; Ibáñez and Martínez-Valderrama, 2018; Martínez-Valderrama et al., 2016). Ibáñez et al. (2014b) reports on general aspects of model construction (e.g. validation) while Ibáñez et al. (2020) provides a Supplementary Document with a full description of all the equations and model parameters. Therefore, in what follows, we only give a brief outline.

In order to carry out a simulation of the model, the user must assign values to 87 parameters of which 81 have real-world counterparts, i.e. are actual biophysical, technical, economic or managerial factors. They are divided into two groups (Fig. 1):

i. System parameters, which allow the user to specify the characteristics of the socio-economic and environmental subsystems (see below) for a given simulation.

ii. Driver parameters, which allow the user to calibrate the driver submodel (see below). This group includes the two factors whose effects and interactions were assessed in the study presented here, namely 'Drought return period' (drrp) and 'Drought severity' (drsv). See Section 2.3.

The model comprises 108 equations which are divided into three submodels (Fig. 1):

i. The driver submodel generates temporal patterns for model drivers throughout the simulation period. By driver we mean a variable that influences the rangeland but is not influenced by it. They are divided into weather drivers, i.e. amount and energy of rainfall and reference evapotranspiration, and economic drivers, i.e. world/regional prices, costs other than supplementary feed and breeding females, and opportunity costs of farmers.

ii. The socio-economic submodel is referred to the whole farming area and comprises the equations for: a) Total number and total area of active farms (each owned by one farmer); b) Supplies of output and old females; c) Demand for supplementary feed; d) External and internal supplies of, and demands for, breeding females; e) Local prices of output, old animals, supplementary feed, and breeding females; f) Total profits in the farming area and profits for an average farmer; and g) Total number of grazing animals (breeding and young females).

iii. The environmental submodel is referred to a representative hectare within the farming area, i.e. a strip of land with homogeneous characteristics which extends from the top to the bottom of a hill. This submodel comprises the equations for: a) Soil moisture; b) Green and dry herbage masses; and c) Remaining soil depth.

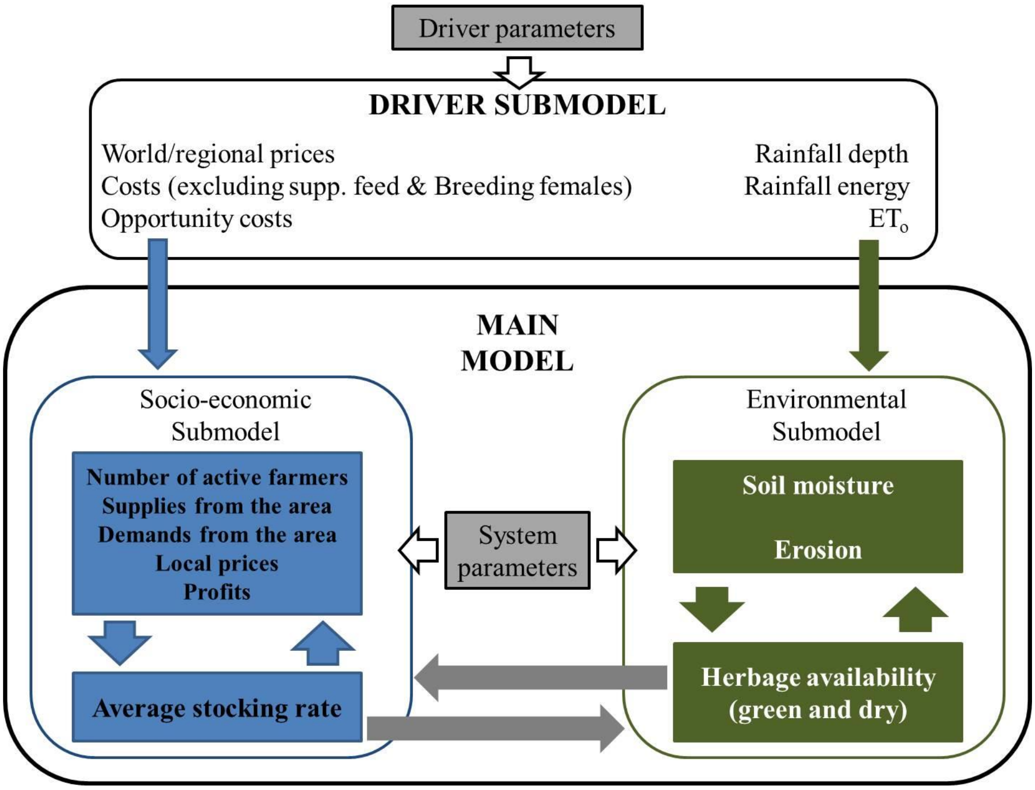

Fig. 1. Schematic diagram of the model. To run the model, the user must assign values to the driver and system parameters (in grey). Socio-economic submodel refers to the whole farming area. Environmental submodel refers to a representative hectare within the farming area.

Submodels are linked as follows (Fig. 1). The average stocking rate across the farming area yielded by the socio-economic submodel is the stocking rate in the hectare represented in the environmental submodel. In this way, economic drivers, farmers' decisions, and local markets influence the availability of pasture, soil moisture and soil erosion. On the other hand, the per hectare herbage availability yielded by the environmental submodel is taken by the socio-economic submodel as the average availability across the farming area. Hence, climate drivers and soil erosion influence costs of production, profits, farmers' decisions, and local markets.

In short, the main processes represented in the model are the following: (i) precipitation and evapotranspiration determine the soil water balance; (ii) standing herbage biomass depends on such a balance and on grazing; (iii) grazing animals reduce herbage biomass by consuming it and by creating bare soil areas through trampling; (iv) the rate of consumption of herbage per animal depends on the availability of herbage, and thus on rainfall patterns.

There are three ways in which farmers may deal with dry periods in the model: (i) animals may receive supplementary feed. The demand for this input depends on the number of animals, the availability of herbage, its local price and profits. (ii) When herbage is scarce, animals may be allowed to lose some weight by restricting supplementation. (iii) Destocking/restocking is possible because the size of the herds only changes by the selling and buying of breeding females (young females only replace old females that leave production). Decisions about the size of the herds are linked to profits and the local price of live animals.

It must be stressed that the management of these three instruments during a given model run depends on the average economic behaviour of farmers, which is specified by means of four system parameters as part of the simulation scenario (Section 2.4).

Farmers enter or leave farming after comparing its expected returns with those from other activities, i.e. with their opportunity cost. Of course, the economic characteristics of farmers also influence these decisions.

Local prices are related to world/regional prices, local supplies and demands, and external demands and supplies, which co-evolve with local prices. Active farmers may receive subsidies which do not depend on stocking rates. The user can determine the factor by which costs increase with water scarcity, for example, because farmers need to purchase water for livestock.

The modelled rangeland could suffer permanent degradation through water erosion, given that it reduces soil water storage capacity and increases topsoil bulk density, thereby reducing herbage production. The erosion rate depends on surface runoff and topsoil bulk density. Surface runoff depends on rainfall intensity, rainfall energy, soil moisture and canopy cover (and thus livestock numbers).

Clearly, it is crucial to care the internal consistency of a multidisciplinary model like this. A lot of effort has gone into ensuring this point, which has been subjected to strong tests in all the versions of the model. Thus, for example, the current version was run under 288,000 different scenarios without a single collapse (Ibáñez et al., 2020).

2.3. Generation of rainfall patterns in the model

As already indicated, the driver submodel includes the equations aimed at generating rainfall patterns throughout the simulation period. We detail these equations here because of their special role in the present study. In what follows, any variable or parameter without specified units is dimensionless.

Rainfall depth (RFDP [mm]; Eq. (1)) in time step ‘t’ is the product of two variables: ‘Does it rain during the time step? yes (1) - no (0)’ (RFYN) and ‘Possible rainfall depth in the time step’ (RFDY [mm]). The former is the outcome of a Bernoulli trial where the ‘yes’ probability, i.e. p = P(RFYN = 1), follows seasonal and interannual cycles (Eqs. 2-3). In turn, RFDY yields the amount of rainfall in a rainy time step, i.e. if RFYN = 1 (Eq. 4). The length of a time step in the model is 0.0078125 yr, i.e. around 2.8 days, which is the shortest that Vensim® (Ventana Systems Inc.), the software used to build and manage the model, offers by default.

$$RFDP_t = RFYN_t \cdot RFDY_t \quad (1)$$

$$RFYN_t = \mathit{bernoulli}\{p\} \quad (2)$$

$$p = rfpm \cdot (1 + rfss \cdot \mathit{sin}\{2\pi \cdot (t - 0.25)\}) \cdot \mathit{min}\{1, 1 + drsv \cdot \mathit{sin}\{2\pi \cdot t/drrp\}\} \quad (3)$$

$$RFDY_t = \mathit{lognormal}\{rfdm, rfdd\} \quad (4)$$

where:

rfpm = Average probability of rainfall during one time step; rfss = Maximum fractional change in the probability of rainfall per time step within a year; drsv = Drought severity, i.e. maximum fractional decrease in the probability of rainfall per time step during a drought; drrp = Drought return period [yr]; rfdm = Average rainfall depth per rainy time step [mm]; rfdd = Standard deviation of rainfall depth across rainy time steps [mm].

The probability, p, that it rains during a given time step results from multiplying two factors (Eq. 3). The first one is the product of the driver parameter rfpm and a sine wave function centred on one whose period is one year. This factor generates intra-annual (seasonal) cycles in the probability of rainfall per time step (Fig. 2a). The term t - 0.25 is used in this factor to make years start in the middle of the dry season, i.e. at the annual minimum of p. The second factor in Eq. (3) superimposes interannual cycles in p, that is, droughts. The upper half of these cycles is truncated to discriminate between normal, i.e. factor = 1, and drought years, i.e. factor < 1 (Fig. 2b).

For a given value of rfpm, the form of these two factors depends on the values given to the driver parameters rfss, drsv and drrp. For the sake of illustration, Fig. 2a compares the form of the first factor under two scenarios: the default scenario of the model and one with a smaller value of rfss, i.e. one where seasonality is milder. Fig. 2b illustrates the form of the second factor under three scenarios: the default scenario, one where drsv is larger, i.e. where droughts are more severe, and a third one where only drrp varies, being larger than in the default scenario, i.e. where the return period of droughts is longer.

The amount of rainfall in a rainy time step, i.e. when RFYN = 1, is sampled from a log-normal distribution whose driver parameters are the mean (rfdm) and standard deviation (rfdd) of the distribution (see Eq. (4) and Fig. 2c). This distribution reflects the typical skewness that characterizes the distribution of precipitation in drylands (Alcalá et al., 2018; Dixon et al., 1989; Williams and Albertson, 2006).

The modelling study presented here evaluated the effects of parameters drsv (drought severity) and drrp (drought return period) on key response variables of the modelled system by analysing the results of many model runs (Section 2.5). The different simulations corresponding to a given climate scenario were obtained by changing the value of the random seed. Note that this seed is involved in determining the outcomes of the Bernoulli trial and the sampling from the log-normal distribution. Similarly, it is involved in the determination of reference evapotranspiration (ET_o) and rainfall energy.

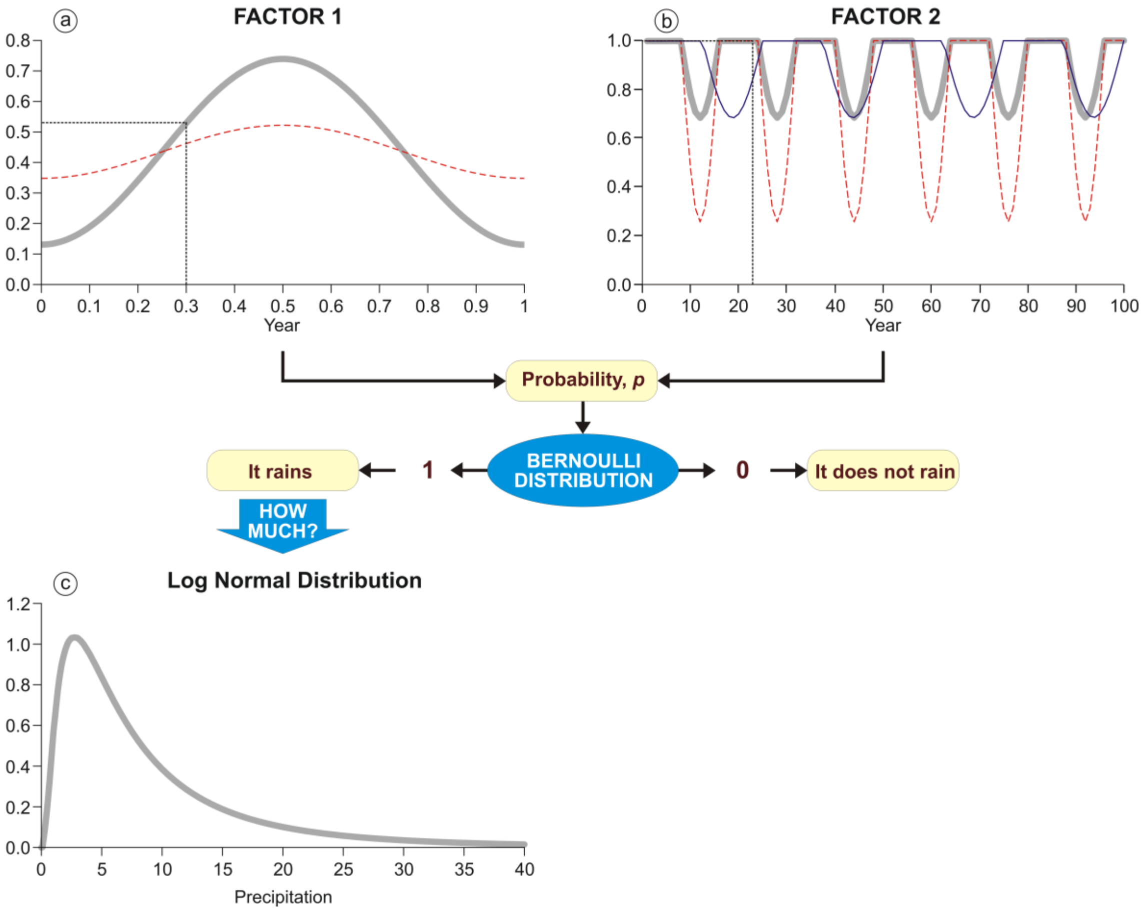

Fig. 2. Functions involved in generating rainfall patterns. (a) Seasonal cycles: solid grey line = default scenario; dotted red line = scenario where seasonality is milder. (b)

Interannual cycles in the probability of rainfall per time step (droughts): solid grey line = default scenario; dotted red line = scenario of severe droughts; blue line = scenario with a longer return period of droughts. (c) Log-normal distribution of rainfall depth in rainy time steps.

2.4. The representation of the economic characteristics of farmers

Farmers' decisions throughout a model run, including those involved in dealing with droughts, depend on their average economic characteristics, which are defined by means of four system parameters. Ibáñez and Martínez-Valderrama (2018) illustrate how these parameters take part in the model and analyse their influence on model's behaviour. However, given the special role that the economic characteristics of farmers have in this study, it is worth revisiting briefly its representation in the model.

The four system parameters in question are:

dfex = Average delay time for farmers to adjust expectations. The higher the value of dfex is in a scenario, the slower farmers will adjust their expectations.

dftg = Average delay time for farmers to achieve targets. The higher the value of dftg is in a scenario, the slower farmers will seek to achieve targets.

sfpc = Average sensitivity of farmers to current prices. The higher the value of sfpc is in a scenario, the greater the extent to which farmers will revise their rate of target achievement when market prices are unfavourable.

sfpf = Average sensitivity of farmers to expected profits. The lower the value of sfpf is in a scenario, the less farmers will react to changes in expected profits.

A simulation scenario where sfpf is low and sfpc, dftg, and dfex are high reflects that the average responsiveness of farmers to changing economic circumstances is low, i.e. that most of the farmers in the area are conservative (widespread conservatism). By contrast, a simulation scenario including the opposite combination of parameter values reflects that the average responsiveness of farmers is high, i.e that most of the farmers are opportunistic (widespread opportunism). With any other combination of parameter values the average responsiveness across farmers will fall between both extremes.

Ibáñez and Martínez-Valderrama (2018) found that the exploitation of grazing resources was optimal only under either a widespread opportunism or a widespread conservatism. The former proved to be optimal from an economic viewpoint, while the latter proved to be optimal from economic, social, and ecological perspectives. See Section 4 for details on how both group decision-making strategies differ in managing the instruments for dealing with droughts represented in the model.

2.5. Default or historic parametric scenario

As already mentioned, the model was initially calibrated for a Spanish dehesa in a representative default or historic state. All the parameter values corresponding to such state can be seen in Ibáñez et al. (2020). Most of these values were derived from field data measured at 22 fenced areas selected from 10 representative farms distributed across the Spanish region of Extremadura, and from semi-structured interviews with their owners. These interviews characterized farmers as mostly conservative, in the sense explained before. Climate data were obtained from the Spanish Meteorological Agency (AEMET). Prices were official figures issued by the Spanish Ministry of Agriculture, Food and Environment. Finally, representative values for some of the remaining parameters were found in the literature. See Ibáñez et al. (2016 and 2014a) and Pulido et al. (2018) for more details about the data sources of the model.

In total, 87% of the default parameter values could be specified as explained. The values for the rest of parameters were assigned after evaluating numerous probe simulations, but rather arbitrarily. Fortunately, model's behaviour turned out to be scarcely sensitive to all these unknown parameters (Ibáñez et al., 2020).

2.6. Sensitivity assessment

In order to evaluate the sensitivity of Spanish dehesas to increases in the severity and frequency of droughts under climate change scenarios, a multi-way ANOVA was carried out on the basis of a great number of model simulations.

The climate scenarios for these simulations were created by modifying the values of seven parameters in relation to their default or historic values; these parameters are presented in Table 1. As can be seen, they are divided into two groups: general climate parameters (five parameters) and drought-related parameters (drsv and drpp).

The general climate parameters were not analysed individually, but as a group. Thus, they took six different sets of values (Table 2), each corresponding to a different block, that is, to a different combination of the levels of two blocking factors:

i. Representative Concentration Pathway (RCP), i.e. scenario of future greenhouse gas emissions, with levels ‘RCP 4.5’, ‘RCP 6.0’ and ‘RCP 8.5’.

ii. Downscaling method, i.e. process by which coarse-resolution Global Climate Models (GCMs) outputs are translated into local climate information, with levels 'ANALOG' and 'SDSM'.

Table 1. Response variables and parameters involved in the multi-way ANOVA

Notation	Description	Units
	Response variables	
AEAF	Average annual earnings per active farmer (over 300 yr)	€ yr^{-1} $farmer^{-1}$
ASTR	Average stocking rate (over 300 yr)	LU ha^{-1}
SODP	Remaining soil depth (at the end of year 300)	mm
	General climate parameters	
rfpm	Average probability of rainfall during one time step	[0, 1]
rfdm	Average rainfall depth per rainy time step	mm
rfdd	Standard deviation of rainfall depth across rainy time steps	mm
retm	Average reference evapotranspiration depth per time step	mm
recv	CV of reference evapotranspiration depth per time step	dimensionless
	Drought-related parameters	
drsv	Drought severity	[0, 1]
drrp	Drought return period	yr

RCPs are the scenarios on which the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is based (IPCC, 2014). In short, emissions in RCP 4.5 peak around 2040 and then decline; in RCP 6.0, they peak around 2080 and then decline; and in RCP 8.5, emissions continue to rise throughout the 21st century (IPCC, 2014; Wayne, 2013).

The two downscaling methods are the statistical methods utilized by the AEMET to provide local scale projections of climate change in Spain. These projections consists of datasets of daily precipitation, and maximum and minimum temperatures for many meteorological stations in Spain, and cover the period 2006-2100. Each dataset results from applying a downscaling method to data provided by a GCM under a RCP, data serviced by the Coupled Model Inter-comparison Project Phase 5. The data for the analysis corresponded to the city of Cáceres (Extremadura, SW Spain). The number of datasets available for each block was variable (see *n* in Table 2). Daily data on ET_o were derived from maximum and minimum temperatures by means of the simplified Hargreaves formulae (Hargreaves and Samani, 1985).

Table 2. Average values of the general climate parameters used in the multi-way ANOVA for each combination of levels of the blocking factors 'RCP' and 'Downscaling method', and their default (historic) values. See Table 1 for the definition of parameters. *n* is the number of datasets used to calculate the averages in each case.

	rfpm	**rfdm**	**rfdd**	**retm**	**recv**	**n**
RPC 4.5 - ANALOG	0.768	4.966	6.914	8.953	0.618	10
RPC 6.0 - ANALOG	0.776	5.126	7.143	8.898	0.619	4
RPC 8.5 - ANALOG	0.744	4.451	6.385	9.381	0.616	7
RPC 4.5 - SDSM	0.442	4.323	4.322	9.730	0.623	10
RPC 6.0 - SDSM	0.445	4.504	4.729	9.720	0.622	5
RPC 8.5 - SDSM	0.431	4.538	4.657	10.088	0.620	10
Default (historic)	0.435	9.768	11.272	7.701	0.25	-

Most datasets included only 365-day years. There were a few including leap years, but in such cases figures corresponding to February 29s were removed. To make these time series match the number of time steps per year in the model, i.e. 128 = 1/Time Step = 1/0.0078125, we summed consecutive daily data by groups of two or three days randomly positioned within each year in the series, i.e. we used a different random permutation of 109 3-day groups and 19 2-day groups for each year. For a small third group of datasets that included 360-day years we used random permutations of 104 3-day groups and 2 2-day groups.

Values of the five general climate parameters were estimated on the basis of the resulting series of precipitation and ET_o (46 values for each parameter). Finally, average values were calculated for each block. These are the values shown in Table 2; the default (historic) values are also showed just for comparison.

Naturally, the two drought-related parameters were treatment factors in the multi-way ANOVA. Three levels were defined for each of them. The levels for drsv were 0.17 (the default value), 0.35 and 0.5 (the last two levels reflect increases in the severity of droughts in relation to the default scenario). In turn, the levels for drrp were 16 (the default value), 12 and 8 yr (the last two levels reflect reductions in the drought return period in relation to the default scenario).

A hundred simulations (replicates) were run for each of the 3·2·3·3 = 54 cells in the analysis. These were obtained by varying the value of the random seed from 1 to 100 (Section 2.3). Thus, the analysis utilized 5,400 model runs. A 300-year simulation period was used for all of them with the aim of enabling long-term processes to clearly manifest their effects, especially those driven by soil erosion. Clearly, this means that our modelling study aimed at exploring the possible behaviour of the modelled system, and not at performing a predictive exercise.

The variables chosen as response variables provide a summary of the behaviour of the entire model throughout a simulation period. Thus, by evaluating their sensitivity to drrp and drsv, the sensitivity of the entire system was assessed. These variables were: i) average profit per farmer over the simulation period, i.e. calculated at the end of year 300, which informs about farmers' economic performance under a given scenario; ii) average stocking rate over the simulation period, which informs about the average level of intensification; and iii) remaining soil depth at the end of year 300, which informs about the level of degradation (Table 1).

In sum, our analysis evaluated the effects of the frequency (drrp) and intensity (drsv) of droughts on the three response variables, and thus on the entire system, under different climate change scenarios. Such evaluation (done outside the model) was based on the values obtained for the response variables in 5,400 model runs, and the values that the blocking and treatment factors took in the corresponding scenarios. Therefore, this study did not need to examine the dynamic behaviour and relationships of model variables throughout the simulations. In order to understand some aspects of the ANOVA results, the time trajectories followed by some variables were checked in a number of simulations (Section 4). However, this was a marginal, non-rigorous procedure done out of mere interest. It would have been laborious to examine in depth the dynamic behaviour of 108 interrelated variables in 5,400 300-year-long simulations. But, in any case, this issue lied beyond the scope of this study.

3. Results

It is worth to start by making some points about the values estimated for the general climate parameters in the climate change scenarios (Table 2), even though these are mere collateral results of the study. The SDSM downscaling method yielded values of the average probability of rainfall during one time step (rfpm) which are in line with the historic value, whereas the ANALOG method yielded higher values. However, both methods approximately halved the historic value of the average rainfall depth per rainy time step (rfdm) for all RCPs. Besides, the SDSM method yielded higher values of the average ET_o per time step (retm) than the ANALOG one, though both methods resulted in values greater than the historic one. Therefore, the six climate change scenarios used in the analysis predict more arid conditions for the study area, the hardest being predicted by the SDSM method. It must also be noted that the ANALOG method yielded the highest values of the standard deviation of rainfall depth across rainy time steps (rfdd), especially under RCPs 4.5 and 6.0.

The multi-way ANOVA evaluated the main effects and all the possible interactions between factors. However, given that 100 simulations were run for each cell, most of the main effects and interactions turned out to be highly significant. Thus, ANOVA tables were scarcely informative, so they have been included in the Supplementary Document (Section SD-1). This document also includes the tables with the values of the cell means represented in Figs. 3 to 6 (Section SD-2).

Fig. 3 shows the estimated means of 'Average Annual Earnings per Active Farmer' (AEAF) in the analysis. AEAF increased with increasing drought severity (drsv) in all blocks. But even the largest increases of AEAF in RCPs 4.5 and 6.0 plus the ANALOG method could be considered as relatively small (around 3,000-4,000 €/yr). The ANALOG method plus RCP 8.5 and the three blocks including the SDSM method resulted in very small increases in AEAF with drsv (around 1,000 €/yr). Note also that, for any given combination of the levels of drpp and drsv, RCPs 4.5 and 6.0 plus the ANALOG method yielded the greatest means of AEAF.

Regarding the return period of droughts (drrp), it only showed some tiny effects on AEAF with RCPs 4.5 and 6.0 plus the ANALOG method, and exclusively when drsv equalled 0.5.

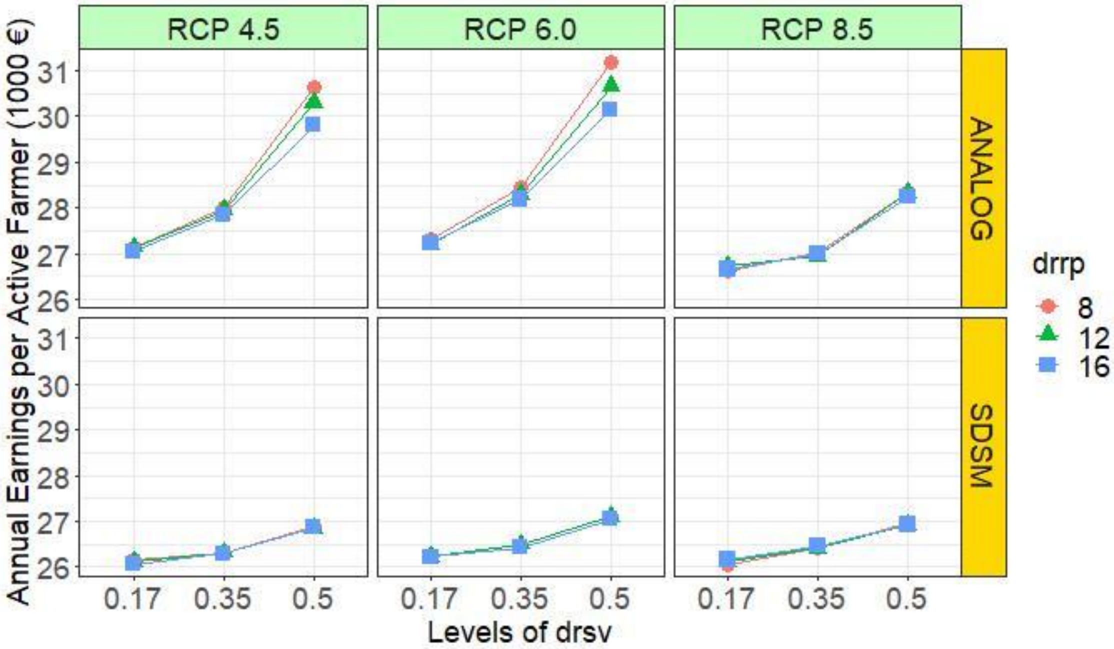

Fig 3. Cell means for Average Annual Earnings per Active Farmer (AEAF) (€). Cells result from the combination of the levels of the blocking factors Representative Concentration Pathway (RCP) and Downscaling method (with levels ANALOG and SDSM), and the treatment factors Drought severity (drsv) and Drought return period (drrp).

In sum, the multi-way ANOVA suggested that the sensitivity of the annual earnings per active farmer to increases in the frequency and severity of droughts under climate change would be low or very low in Spanish dehesas.

Fig. 4 shows that variations in cell means of 'Average Stocking Rate' (ASTR) were qualitatively similar to those of AEAF, except that this variable decreased as drsv increased. However, reductions were extremely small in general. Note that the greatest one only ranged from 0.6 to 0.55 LU·ha^{-1} (red line under RCP 6.0 plus the ANALOG method). Thus, the sensitivity of the stocking rate to increases in the frequency and severity of droughts under climate change scenarios would be negligible in Spanish dehesas.

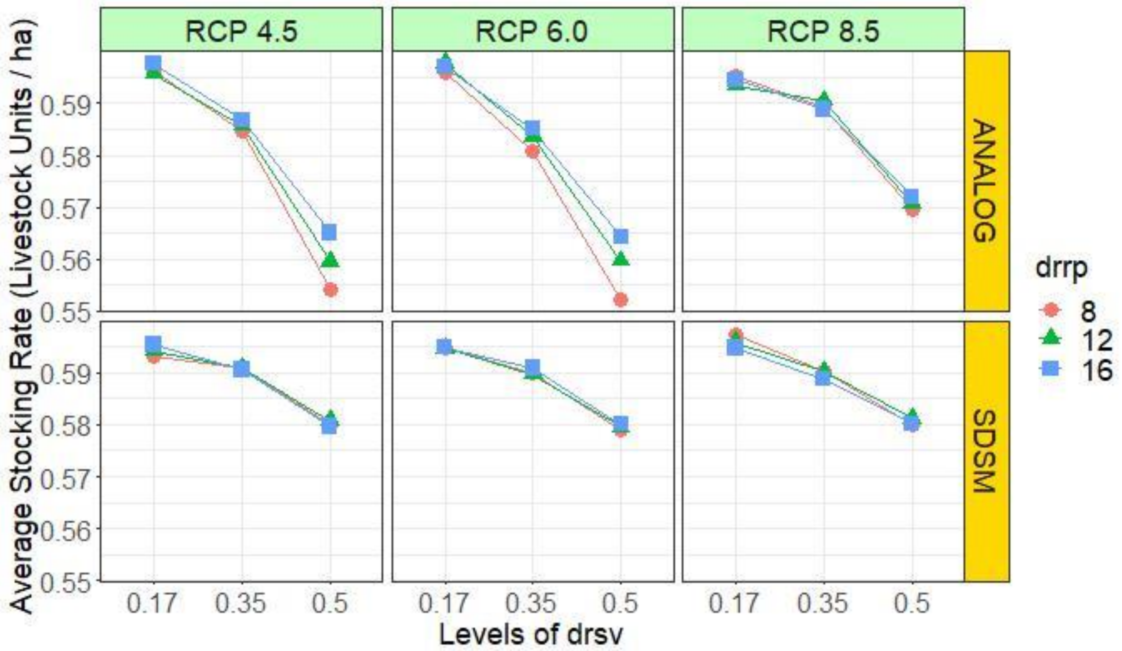

Fig. 4. Cell means for Average Stocking Rate (ASTR) (LU·ha^{-1}). Cells result from the combination of the levels of the blocking factors Representative Concentration Pathway (RCP) and Downscaling method (with levels ANALOG and SDSM), and the treatment factors Drought severity (drsv) and Drought return period (drrp).

A histogram of the 5,400 values of 'Remaining Soil Depth' (SODP) used in the analysis showed that they were divided into two groups, each corresponding to a downscaling method. These groups followed normal distributions whose means and variances were noticeably different. Thus, in order to verify the assumption of homogeneity of variances, a different multi-way ANOVA was performed for each method. Results are shown in Figs. 5 and 6.

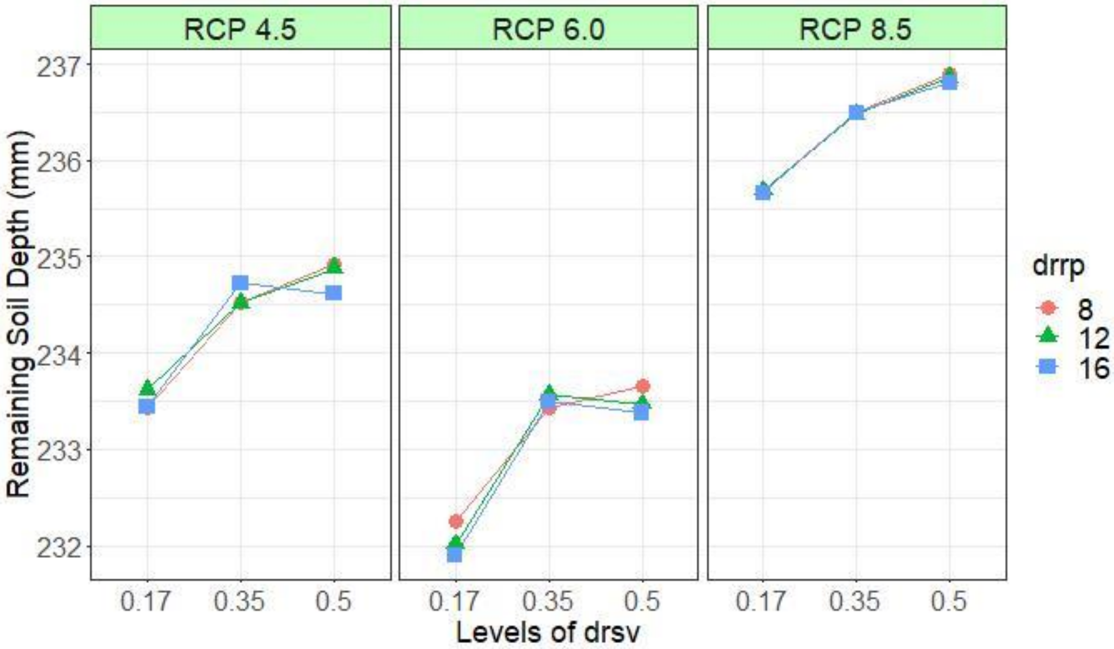

Fig. 5. Cell means for Remaining Soil Depth (SODP) (mm). Cells result from the combination of the levels of the blocking factors Representative Concentration Pathway (RCP) and ANALOG Downscaling method, and the treatment factors Drought severity (drsv) and Drought return period (drrp).

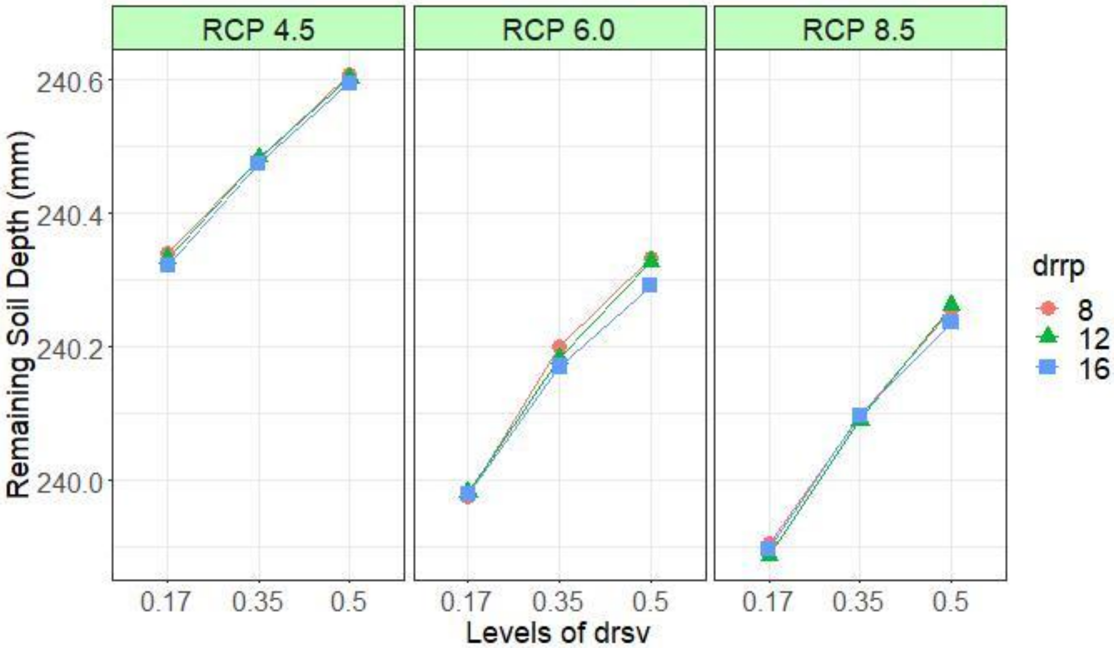

Fig. 6. Cell means for Remaining Soil Depth (SODP) (mm). Cells result from the combination of the levels of the blocking factors Representative Concentration Pathway (RCP) and SDSM Downscaling method, and the treatment factors Drought severity (drsv) and Drought return period (drrp).

To better understand these figures, it must be taken into account that the initial value of SODP, i.e. the initial soil depth, was 234 mm in all simulations. Therefore, soil depth increased throughout the simulation period in most cells, though slightly (6 mm in 300 years at most). Only in 12 out of 54 cells there were accumulated losses of soil, though very little (around 2 mm in 300 years at most).

Thus, the analysis suggested that, in general, the sensitivity of soil depth to increases in the frequency and severity of droughts under climate change would be very low in Spanish dehesas. More specifically, it would be extremely unlikely that the worsening of droughts will increase soil erosion.

4. Discussion

The main finding of our modelling study is that the sensitivity of Spanish dehesas, and thus their vulnerability, to increases in the frequency and severity of droughts under climate change would be low. Note that this finding does neither mean that nothing will happen during a given drought, nor that Spanish dehesas are insensitive to climate change, in general, as proposed by Golodets et al. (2013), who found that the vulnerability of herbaceous productivity to climate change in Mediterranean rangelands would be unexpectedly low.

A crucial factor in our study was the utilization of a multidisciplinary model which includes instruments to deal with droughts along with a diversity of ways in which farmers can manage them. Strategies for dealing with dry periods can be divided into two types (Le Houérou, 1996): (a) drought-evading strategies, like nomadism and transhumance, consisting in taking livestock where pasture is more abundant (Vigan et al., 2017); and (b) drought-enduring strategies, based on maintaining financial viability while retaining as many reproductive units as possible for post-drought recovery (Brown et al., 2016). Examples of the latter are: (i) providing supplementary feed; (ii) Allowing weight losses in animals within safe margins; (iii) destocking/restocking; (iv) leading animals to browse shrubs and trees to provide an extra feed source; (v) changing herd composition to better adapt species or breeds; or (vi), harvesting rainfall and runoff, diverting rivers or streams, and/or taking advantage of shallow groundwater infiltration, in cases where water availability is a critical factor.

In Spain, drought-evading strategies are in decay (Carmona et al., 2013) and farmers generally use a combination of drought-enduring strategies, where supplementing plays an increasingly important role (Soto et al., 2016).

The model allows farmers to employ the drought-enduring strategies (i), (ii) and (iii) (Section 2.2) according to their average economic characteristics, which is defined as part of the simulation scenario (Section 2.4). In all the model runs used for this study the scenarios reflected a widespread conservatism, i.e. that most of the farmers were relatively unresponsive to changing economic circumstances. This agrees with the description that farmers in the study area made of themselves in interviews (Section 2.5). With such specification, the model ensures that farmers hardly changed the size of their herds, and allowed the state of their animals to deteriorate somewhat only if the price of supplementary feed increased considerably. If farmers had been defined as mostly opportunistic (widespread opportunism), they had prioritized the destocking/restocking strategy, and had allowed animals to lose weight to a much greater extent.

Ibáñez and Martínez-Valderrama (2018) showed that a widespread conservatism is optimal from economic, social, and ecological viewpoints because it smooths the effects of shocks to the system, thereby preventing turbulences in markets, a problem which is signalled as one of the main drawbacks of opportunistic strategies (Campbell et al., 2000). Quaas et al. (2007) also found that a conservative strategy provides natural insurance for risk-averse farmers.

In sum, our study suggests that the low sensitivity of Spanish dehesas to the worsening of droughts could be explained by a widespread conservative use of supplementation. This group strategy, which was found to be effective for coping with periods of herbage scarcity under a historic or no-climate-change scenario (Ibáñez et al., 2020), would continue to be so in the more arid conditions foreseen for the area.

Although it was not strictly needed for our sensitivity assessment, we tried to explain the main results observed in the response variables (Section 3). The means that ‘Average Annual Earnings per Active Farmer’ (AEAF) took in each block (Fig. 3) had a direct relationship with the values that the variability in rainfall intensity took in the corresponding climate scenario (see parameter rfdd in Table 2). Given that extreme low values of rainfall intensity are truncated at zero, a high variability in this variable is mainly manifested by a greater frequency of events of heavy rain. Therefore, it could be expected that soil moisture, and thus herbage production, increased, on average, as rfdd increased in the scenarios. In effect, this point, which would explain the positive correlation between AEAF and rfdd, was checked in a number of simulations of the analysis.

The response variable ‘Remaining soil depth’ (SODP) also was directly related to rfdd. Indeed, soil depth increased more under the SDSM method than under the ANALOG method (Figs. 5 and 6), being that the values of rfdd were smaller under the former than under the latter (Table 2). Besides, the combination of RCP 6.0 and the ANALOG method, the only situation leading to generalized, though tiny, losses of soil, corresponded with the highest value of rfdd. This agrees with the results of a previous sensitivity analysis of the model which showed that the main factor affecting soil erosion is rainfall variability (Ibáñez et al., 2020).

We formed an idea about why AEAF increased with the severity of droughts (parameter drsv) by observing the time trajectories of some variables in a number of simulations. As expected, the higher was the value of drsv in a scenario, the greater were the shortages of herbage production, and thus the demands for supplementary feed, during the droughts occurring throughout the corresponding simulation. In severe droughts, at least in the sample of simulations observed, the market did not react with the necessary flexibility, so the supply of supplementary feed did not match the demand, and animals ended up receiving less feed than in mild droughts. Thus, in such simulations, the condition of the animals was worse, output production was less, and output price was higher under severe droughts than under mild droughts. In the former case, the increases in the output price outweighed the negative economic effects of the reductions in output production and the rises in the costs of animal feeding, and hence average profits slightly escalated. The corollary is that an increase in the severity of droughts with climate change could affect consumers negatively.

Finally, soil depth presumably increased with the severity of droughts because the abundance of this type of droughts reduced the total amount of rain fallen throughout the simulation period in relation to scenarios of milder droughts. In effect, this was so in the sample of observed simulations even though the exposure of the soil was greater due to a relative decrease in vegetation cover.

An advantage of the study presented here is that it was based on a multidisciplinary integrated model, so it made an assessment of sensitivities by taking into account a large number of well-known processes corresponding to different disciplines. We have not found any other model integrating as many aspects of a commercial rangeland as ours.

Thus, for example, Baumgärtner and Quaas (2009), Freier et al. (2011), Iglesias et al. (2016), and Müller et al. (2011), in order to study the impact of droughts in rangelands, utilize models representing grass growth, biomass stock, livestock yields, profits, amount of supplementary feed or the number of animals, but neglect representing variations in the numbers of active farmers, erosion, or price formation mechanisms.

However, multidisciplinary integrated models have their limitations too. The representation of processes must be simplified in order make manageable the final model. Thus, such representations may be deemed to be simplistic by the experts in each of the disciplines involved. Even those appreciating the holistic factor provided by multidisciplinary integrated models may label them as speculative. And, certainly, the number of unknowns grows with the number of multidisciplinary processes represented. However, single-discipline models that ignore the evident effects of processes corresponding to other disciplines are speculative too. Just for example, it is speculative to state that some result would apply after assuming that prices are constant, or after completely ignoring prices. In this regard, we only say here the obvious, that all models are wrong (Sterman, 2002), that all seek to be useful, and that all complement each other.

Clearly, there are a number of details that can be revised in our model. In fact, every new version incorporates improvements. The aspect requiring the greatest development is the representation of environmental degradation. Reflecting this degradation exclusively by soil erosion is a clear misrepresentation in the current version of the model.

In any case, we hope that our study can shed some light on the effectiveness of management strategies to cope with forage risks in Mediterranean commercial rangelands, or even in other regions of the world, with the special role of supplementation (Campbell et al., 2000; Kachergis et al., 2014; Sandford and Scoones, 2006; Torell et al., 2010). However, the question arises: could supplementary feeding be generalized worldwide as a strategy for coping with weather variability in extensive livestock systems? The answer seems to be 'no'. Nearly two thirds EU's cereals production are used for animal feed (European Commission, 2015) and globally the figure is 36% (Cassidy et al., 2013). Additionally, around three-quarters of soy worldwide production is used for animal feed (Wang et al., 2018; WWF, 2014). Only in Europe, such a use involves more than 27 million tons per year (de Visser et al., 2014; WWF, 2014). Importing soya into the European Union from South America (Boerema et al., 2016; de Visser et al., 2014) to feed its livestock entails the expansion of soybean cultivation land. This happens mainly in pastures, displacing cattle ranching to forest areas and the savannah (Smaling et al., 2008), or to previously uncultivated ecosystems which lead to direct deforestation (Lathuillière et al., 2014; Olsen and Bishop, 2009), in a clear example of the domino effect that triggers land use changes thousands of miles away (Lambin and Meyfroidt, 2011). But, if supplementation cannot be the solution everywhere, are then the poorest in the less favoured drylands irremediably doomed to suffer the effects of droughts indefinitely? Although most of this feed is intended for industrial livestock farming, there are examples where its massive use causes environmental degradation (Martínez-Valderrama et al., 2018). Determining the appropriate amount of feed to be used by extensive livestock farming in order to mitigate the impact of droughts, but minimising the on-site and off-site effects, is a key issue that demonstrates the connection between different production systems and the need for a global and transdisciplinary approach to study food systems sustainability.

5. Conclusions

By means of a multidisciplinary integrated model 5,400 climate scenarios have been implemented to assess the impact on three key response variables in dehesas, covering both economic and environmental aspects. These Mediterranean rangelands face with uncertainty the particularly acute climate change expected in the region.

The scenarios and their effects feed into a multi-way ANOVA test. This has shown that most of the main effects and interactions turned out to be highly significant although sensitivity of response variables to increases in the frequency and severity of droughts under climate change would be low or very low.

Our main conclusion is that minimizing changes in the size of the herds, and using supplementary feeding would provide Mediterranean commercial rangelands (like Spanish dehesas) with adaptive capacity to increases in the frequency and severity of droughts linked to climate change. Thus, under these drought-enduring strategies, the sensitivity, and consequently the vulnerability, of this type of systems to the worsening of droughts with climate change would be low.

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