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System Dynamics Tools to Study Mediterranean Rangeland's Sustainability

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Abstract

15 Rangelands are a key resource present all over the world as it covers half of emerged lands. They are even more important in drylands, where they cover 48% of the total area. Intensification and the additional pressure added by climate change pushes these systems 18 towards desertification. Over the last two decades, we have developed and applied System Dynamics (SD) models for the study of Mediterranean grasslands. In addition, we have developed procedures and analysis tools, such as global sensitivity analysis, stability analysis 21 condition, or risk analysis, in order to detect the main drivers of these socio-ecological systems and provide indicators about their long-term sustainability. This paper reviews these works, their scientific background and the most relevant conclusions, including purely technical and 24 rangeland-related ones as well as our experience as systemic modelers in a world driven by field specialists.

27 **Keywords:** Drylands; Mediterranean; Early Warning Systems; Sensitivity Analysis; Desertification

30 **1. Introduction**

Rangelands can be defined as those ecosystems where humans have managed their vegetation cover through the presence of livestock in order to obtain economic benefits [1]. This is the 33 predominant land use in the world, occupying half of the emerged lands. Its extension is about 29 million km², of which 63% is located in drylands [2]. They cover about 70% of the needs of domestic ruminants [3] and are a key resource for developing countries, where they are the main 36 support for the 1.2 billion people who survive on less than \$1 a day [4].

The degradation of grazing systems can therefore affect large areas of the planet and the most vulnerable population. Many of these ecosystems are located on marginal, less fertile land, 39 where increased livestock densities alter ecosystem structure and functions [5], leading to deterioration of their economic and biological productivity. The impact of grazing increases with aridity [6]. Substantial degradation is occurring across the world's arid and semi-arid 42 rangelands [7–9] and the expected increasing frequency and duration of droughts [7,10,11] and the foreseeable aridification of mid-latitudes [12,13], as a consequence of global warming, pose major threats to rangelands.

45 This work focuses on the Mediterranean region, where rangelands occupy 48% of the territory [14] and the threat of global warming is particularly acute [15,16]. In these ecosystems, the varied botanical diversity is noteworthy, including grasslands and meadows, which occupy 48 20% of the total [17], and more or less dense shrubs and forests where the main use is for livestock and the dominant species are goats and sheep. The degradation of the Mediterranean rangelands belongs to the scope of desertification, since it occurs in drylands (specifically dry 51 sub-humid, semi-arid and arid areas) and is a consequence of climatic variations and economic activities, as states the United Nations definition of desertification[18] [18]. Although some authors questioned the possibility of desertification in Europe [19], the reality is that the 54 European Union considers it a growing threat [20]. In countries like Spain, agropastoral systems and abandoned rangelands were recognized as already degraded scenarios or at risk of desertification [21,22]. However, the current threat of desertification is more linked to 57 macrofarms [23,24] and extensive livestock farming is more a solution than a problem [25].

This shows that both desertification and rangeland use are complex issues. One of the 60 main causes of quantitative and/or qualitative degradation is overgrazing as a result of increased livestock loading. Numerous works report the erosion processes triggered after the loss of plant cover, or the loss of fodder species [5,26–29]. Simultaneously, opposite forces operate in the 63 territory, which allows us to glimpse that desertification is a complex phenomenon that requires a very fine adjustment in the intensity of land use. In fact, rural abandonment and, therefore, undergrazing, is another typical source of degradation in the northern Mediterranean. Shrub encroachment and the invasion of woody vegetation give rise to the so called 'green deserts'

66 [30], as unproductive, from the socio-economic point of view, as the territories where primary productivity has been reduced.

69 In addition, the rural outflow and lack of grazing that prevented the accumulation of
 72 plant biomass, has created enormous extensions of homogeneous forest masses with hardly any discontinuities with increased fuel loads [31], resulting in fire-prone landscapes [32] combined with global warming, lead to increased higher fire risk, longer fire seasons and more frequent
 75 large, severe fires [33–35]. Although low intensity and low frequency fires have always occurred naturally and play a regulatory role in Mediterranean ecosystems (against phytotoxic agents, promoting seed germination, etc.), when their virulence and recurrence increase (median fire return has been reduced from ~30 to ~10 years in some instances [36], they cause serious damage by exposing the soil to heavy rainfall, preventing seeders from replenishing seed banks [37], depleting re-sprouters bud banks [38], and/or favoring invasive species [39].

78 The economic and environmental importance of rangelands and the challenges they face (climate change, intensification, land-use change, or abandonment) is a relevant field of research. Here we: (i) we point out the utilities of System Dynamics (SD) for tackling such a
 81 complex problem; (ii) we present the SD models developed for different cases of Mediterranean grasslands (Fig. 1), paying special attention to dehesa rangelands, i.e., an agro-silvo-pastoral system resulting from the progressive clearing of the original forest of oaks and/or cork oaks
 84 and covering some 90,000 km² of the southwest of the Iberian Peninsula [40]; (iii) We describe the analysis procedures developed to study the stability of these socio-ecosystems and the factors that most influence it; (iv) Finally, we present some of the main findings in the light of
 87 these analyses and modeling carried out.



90 **Figure 1.** Location of the case studies. Several SD models have been implemented in dehesa rangelands (SW Spain). We have also studied grasslands in the SE of the Iberian Peninsula (Sierra de Filabres), characterized by their aridity and low livestock density. The grazing lands

93 of Lagadas (Greece) have allowed us to apply the models in a more eastern European area. Finally, we have analyzed the degradation processes of the North African steppes, dominated by alfa grass (*Macrochloa tenacissima* L.) steppes.

96

2. An appropriate research field for System Dynamics

99 The study of the sustainability of rangelands (or desertification, which would be its opposite) requires the use of comprehensive tools and a multidisciplinary approach, since various disciplines such as ecology, economics or agronomy are involved in its understanding and management. The need for a holistic approach in complex socio-ecosystems is recurrent [41–
102 48], and SD is a suitable tools for this challenge.

105 SD is a modelling methodology grounded on the theories of nonlinear dynamical systems and feedback control developed in mathematics, physics, and engineering. SD states that the main, but easily-overlooked, cause of the behaviour of a complex system lies in its underlying structure of relationships, which includes feedback loops, non-linear relations, delays and decision rules. Formally, a SD model is a set of first-order
108 ordinary differential equations that makes a stock-and-flow representation of the studied system; stock variables show the state of the system over time, and flow variables represent the processes that change the stocks [49,50]. The main advantages of SD are
111 [51,52]: (i) it improves system understanding, and develop system thinking skills, even from the first stage of its development as causal or sketch diagrams; ii) SD models can incorporate empirical and process-based approaches, and help integrate interdisciplinary
114 knowledge, iii) the SD literature provides abundant information about related methodologies; and iv) user-friendly software platforms allow easy access for non-modeller users.

117 The use of qualitative information is particularly useful in drylands where, available data are limited [53]. SD is particularly useful when the system may face situations that have not previously occurred, i.e., its desertification. For such a task it is required to know the full
120 range of behavior of the variables involved in the system. An example that can help to illustrate this critical aspect is the influence of soil quantity on biomass primary productivity (Fig. 2). The loss of soil through erosion reduces the moisture content and availability of nutrients, and
123 consequently the production of biomass falls. Usual information available to characterize the soil-productivity relationship covers the central part of the function, i.e., where the system is productive (red line in Fig. 2). However, getting information on this function at the extremes is not so simple. It is in these uncomfortable parts of the function where the contribution of the SD
126 is paramount, since it allows the implementation of hypotheses about how systems can work in

critical situations that were initially inconceivable. On the one hand, we know that primary productivity will not grow indefinitely, however much soil there is, i.e., the function becomes saturated at some point. On the other hand, and this is where the problem of desertification lies, there will be a soil threshold below which the system becomes unproductive. Hence, at some point, the function becomes zero (Soil_{\min} in Fig. 2). As Sterman (2000) [50] puts it, the relationships between variables expressed by means of multiplicative factors are more realistic than their linear alternative when the equations are subjected to extreme conditions. This is precisely what happens when rangelands are degraded.

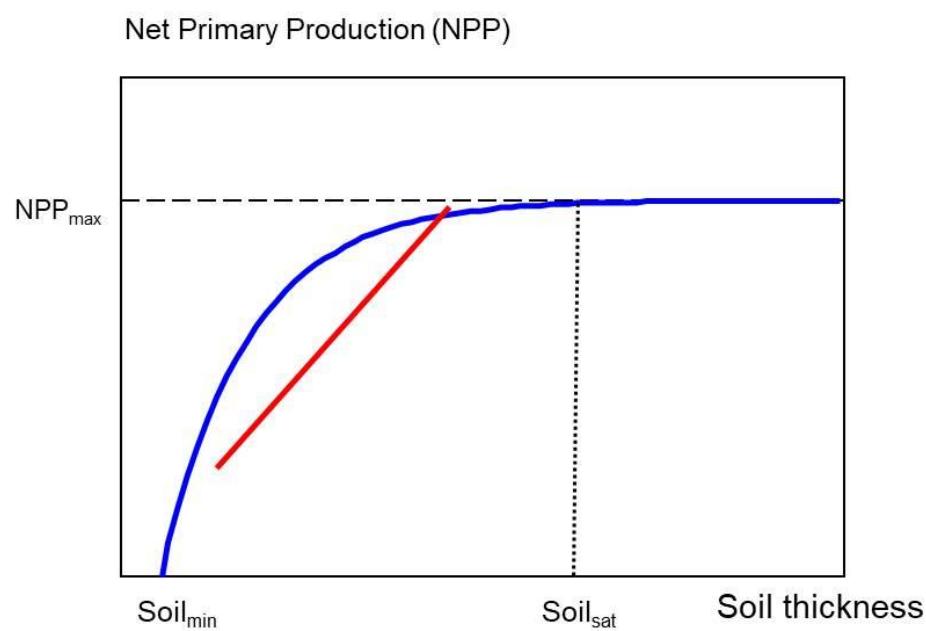


Figure 2. Net Primary Production-Soil thickness non-linear function (blue line) that takes into account minimum soil thickness for grass growth (Soil_{\min}) and soil thickness from which grass growth stabilizes (Soil_{sat}), compared to the conventional linear function (red line) which overlooks the behavior of the function for its extreme values.

SD aims to build dynamic, complex and comprehensive models capable of exploring the long-term impacts of alternative decisions, taking into account the laxity of the laws regulating the behavior of socio-ecological systems and the scarcity of data [54]. In addition, SD is a flexible enough tool to support different data sources and to accommodate multiple analyses. Thus, it is possible to use statistical or stochastic models within its structure and, as we will present later, program routines to implement advanced sensitivity analyses, optimizations and probability calculations.

150

3. A suite of models for assessing rangeland desertification.

153 3.1. A Generic Desertification Model (GDM).

The conceptual paradigm of the SD models implemented to study rangelands stability is the classic models of predator-prey ecology of Lotka [55] and Volterra [56]. We have followed the work of Noy-Meir, who considered extensive livestock systems as a specific case of predator-prey systems [57,58], and those of Thornes [59,60], who addressed the study of erosion as an ecological relationship of competition for water between eroded soil and plant cover.

159 These ideas inspired the formulation of a GDM (see complete description in Ibáñez et al. (2008) [61]) that consists on an eight-equation dynamic model of a generic human–resource system. Briefly, the resource (N) plays the role of prey and the consumption units (U) that 162 exploit it are the predators. The N renewal depends on the climate, the N stock and a limiting factor (S), so called because its level is decisive for the survival of the exploited resource. Reciprocally, the level of N affects the regeneration of S, which also depends on U. In this way 165 S and N have a common destiny: if one does well, the other also does well, but if the degradation of one of them is triggered, then the other is also dragged along. The exploitation of N generates profits through a production function that also requires capital (K). As profit 168 increases, so does U and N consumption; this mechanism also works in the opposite direction. The evolution of U, K and N demand per unit of consumption follows a hill-climbing heuristic, i.e., is driven by the pursue of a dynamic target (e.g. desired U) [50] that depends on 171 profitability and, as in the case of U, on the opportunity cost (O), i.e., the average alternative rent outside the current economic activity.

174 The GDM supports the cyclical behavior of predators and prey. In nature the increase of prey makes the predators grow at their expense reducing their number. When they run out of food, the predator population falls and the prey population recovers, returning to the beginning 177 of the cycle. However, the GDM can reproduce other types of dynamics. In the case of socio-ecological systems the signs of scarcity are bypassed. The profit generated, which depends on prices, costs, and subsidies, allows using inputs that replace the lost resource (e.g., feed can 180 replace the shortage of grass) and create a sense of prosperity even though the environment is degrading. Guided by a misleading abundance the resource can be overexploited, hastening its degradation and causing irreparable damage to the system by crossing critical S thresholds (e.g., loss of fertile soil). This alternative behavior manifests itself in the form of unsustainable 183 exponential growths that can lead to the collapse of the resource, that is, to the desertification of the system.

186 3.2. DESPAS model

The adaptation of the GDM for the understanding of rangeland grazing, which seeks to study desertification processes due to overexploitation of pasturelands, gave rise to the DESPAS 189 model (the Spanish acronym for desertification by overgrazing) [62,63]. The structure of

DESPAS is shown in Figure 3. The model contemplates a single-species livestock herd composed of breeding females, (which serves as the capital, K, of the GDM) with mean and constant physiological states and nutritional requirements. The grass (the predatory resource) consumed by the animals is modulated by its availability. This function, called the functional response of livestock, can adopt various formulations [64] and determines, taking into account animal's energy requirements, the level of supplementary feeding required (see feed sub-model, Fig. 6). It is assumed that these are commercial farms (GDM consumption units), and that all the animals meet their caloric needs in order to maximize their yield. Feed consumption determines the profit and loss account of the farm, since the expenditure on supplementary feeding is the most important. There is a feedback loop in which good economic results encourage the arrival of new farmers in the area or the intensification of the stocking density, leading to greater inputs of supplementary feed, reducing profits and therefore discouraging the growth of livestock farming in the area.

The grass is composed of a single perennial species. Although herbaceous species are annual, seed banks, underground stems or rhizomes allow them to be considered as a perennial species since the current biomass determines the biomass of the following year [58]. Under this condition, along with the uniformity of climatic conditions assumed earlier, the primary production of grass can be satisfactorily represented by means of the logistic function. The outflows from this stock are grazing and grass decomposition, which is linearly proportional to the quantity of biomass present.

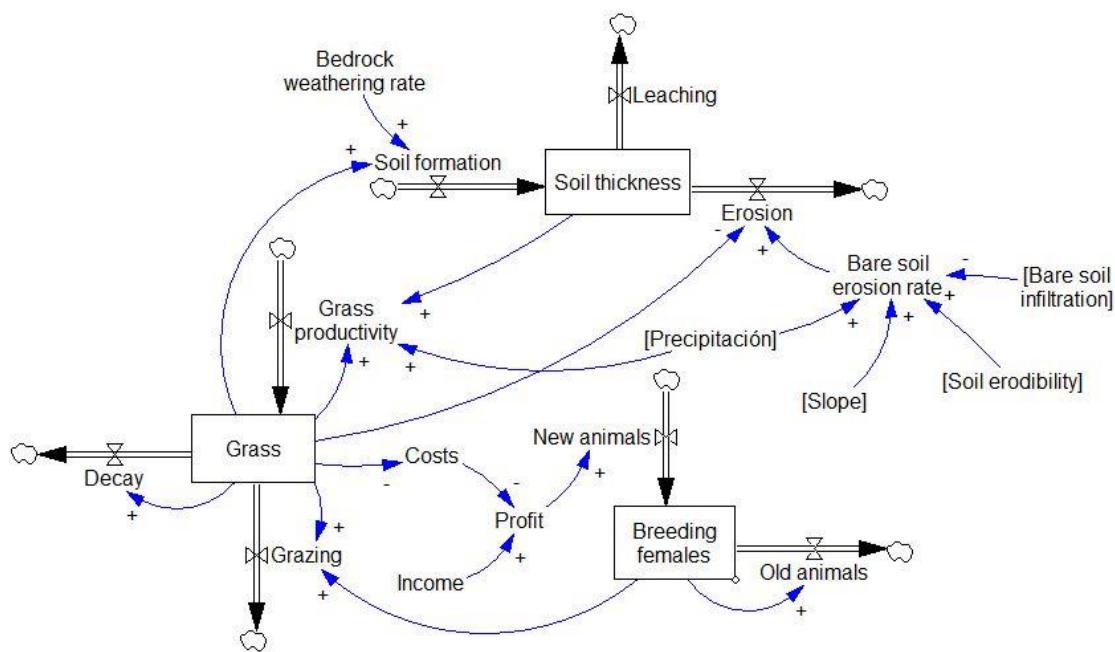
The reduction of plant cover due to grazing exposes the soil to the erosive effect of rain. Runoff, which is the erosive agent considered, depends on soil infiltration, the slope of the land and soil erodibility [65–67]. The resulting relation between plant cover and soil loss are compatible with those given by Elwell and Stocking (1976) [68], a robust empirical relationship in which erosion is maximum with bare soil and declines exponentially as plant cover increases.

Soil thickness depends on two other processes. On the one hand, soil formation from bedrock (weathering rate) and the decomposition of vegetation and, on the other, the leaching rate, i.e., the loss of water-soluble plant nutrients from the soil due to rain. The stock of this limiting factor determines grass productivity, forming a positive feedback mechanism between soil and vegetation. If the soil is kept above certain thicknesses, the system's biomass productivity is reinforced: more soil>more fertility>more plant cover>more protection against erosion>more soil. However, if the soil begins to be lost, the direction of the loop is reversed (less soil>less vegetation cover>less soil), leading to the degradation of the vegetation-soil subsystem.

Changes in livestock stock are based on the economic rationality of the farmer: when the incomes exceed the costs per breeding female (which depend on the amount of supplementary feeding, i.e., the amount of grass consumed by the livestock) then the number of

228 animals is increased and vice versa. Finally, destocking depends on useful breeding life of

females.



231 **Figure 3.** Sketch diagram of DESPAS model. The causal relationships between variables can be

234 positive (i.e., direct, since the changes occur in the same direction: an increase/decrease in the explanatory variable produces an increase/decrease in the explained variable), or negative (i.e., indirect: an increase in the explanatory variable produces a decrease in the explained variable or vice versa). In the case of the flow variables that fill or empty the level variables (box variables) the relationship is, respectively, positive or negative. This network of causal relationships creates feedback loops in the system. Depending on their interaction, one or the other dynamics

237 of the system results.

3.3. Extensions of the DESPAS model.

240 The design of a model depends on its purpose. This, however, may change over time as new situations arise. That is why DESPAS has been refined, extended and sometimes even simplified in order to study different cases. The following sub-models have been implemented:

243 (i) soil moisture, runoff production and its erosive power; (ii) Shrubs–grass competition; (iii) Supplementary feeding; (iv) Farmers' behaviour; and (v) Price forming mechanism. In addition, we refer in this section to the temporal and spatial scales of the models. While the latter has 246 been maintained in all the models, the different methodological developments and processes included have led us to modify the former.

249 *Soil moisture, runoff and erosion.*

In DESPAS, soil thickness is used as a limiting factor. However, in drylands it is more accurate to use water as a limiting factor. For this purpose, the soil moisture level variable was included 252 in the model [69,70]. This makes it possible to implement a water erosion mechanism (Fig. 4) inspired by the analogy used by Thornes (1985) [59] to consider that runoff and soil compete 255 for water. In fact, the better the soil absorption conditions and the more spaced the water falls, the less runoff is left to act as an erosive factor.

Soil moisture results from the balance between infiltration, evapotranspiration and soil 258 drainage; these three flows are naturally conditioned by the availability of water in the soil. The purpose of this water balance is to determine runoff, that is, water that cannot be trapped by soil pores and circulates freely on the surface. Runoff flow determines the rate of erosion.

The three initial flows are determined by two factors. First, they depend on the free 261 space that the soil has to store the water. If all the pores of the soil are filled with water (soil moisture saturation) then there is no infiltration and all the water that falls becomes runoff and triggers soil erosion. Soil field capacity is the amount of soil moisture or water content held in 264 soil after excess water has drained away; a sandy soil drains more water than a clay soil. Finally, the water used by the plants and reflected by the rate of evapotranspiration is the available water between the field capacity and the wilting point. The second factor is the rainfall torrentiality; 267 i.e., how it is distributed over time. Even if the soil has a large storage capacity, if too much water falls in a short period of time, it cannot absorb it. On the other side, if the rain falls in a more distributed pattern (a lower torrential flow), then a greater fraction of the precipitation can 270 be absorbed.

Finally, vegetation cover continues to play an essential role in erosion control. This is reflected in the model by considering that the infiltration rate is linked to the percentage of 273 vegetation cover. Its protecting capacity follows the exponential behavior described in the previous section. The higher this is, the more precipitation is intercepted and retained, which translates into greater infiltration rate.

276 The sub-model adds a further nuance to soil erosion, since it considers that the erosion rate decreases as soil is lost. In other words, the deeper layers of soil exposed by erosion are more compact because they contain fewer pores. Although this implies greater runoff, it also 279 means that the erodibility of the soil is lower and therefore the erosion rate is reduced.

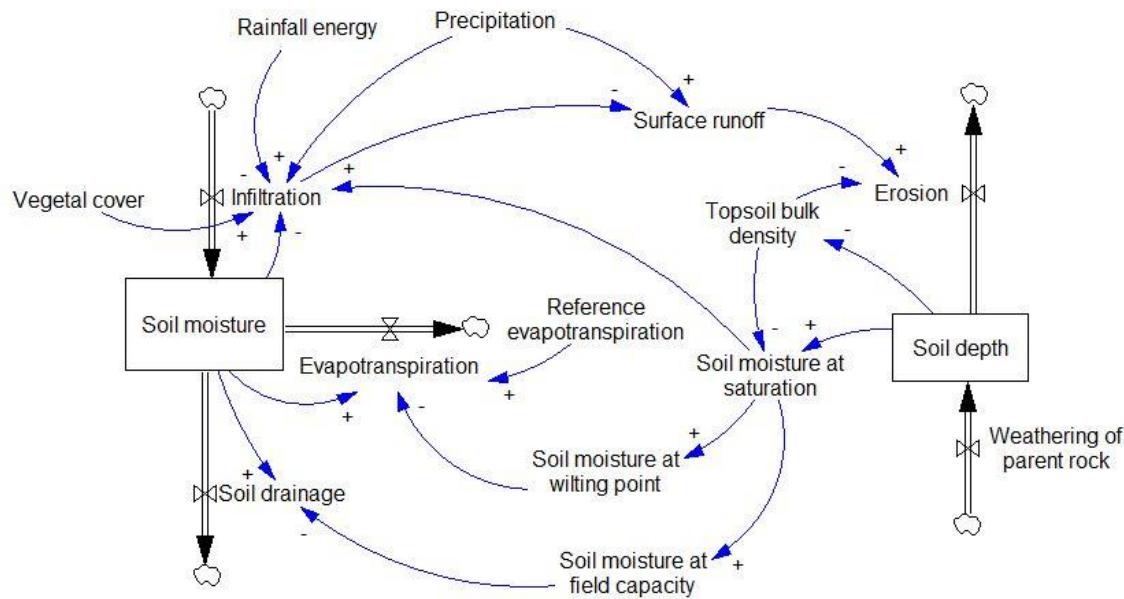


Figure 4. Soil moisture sketch and its influence on the erosion rate. The empirical formulation used in DESPAS, which relates vegetation cover to erosion rate, was replaced by a much more mechanistic approach in which soil water fluxes are detailed in order to determine surface runoff.

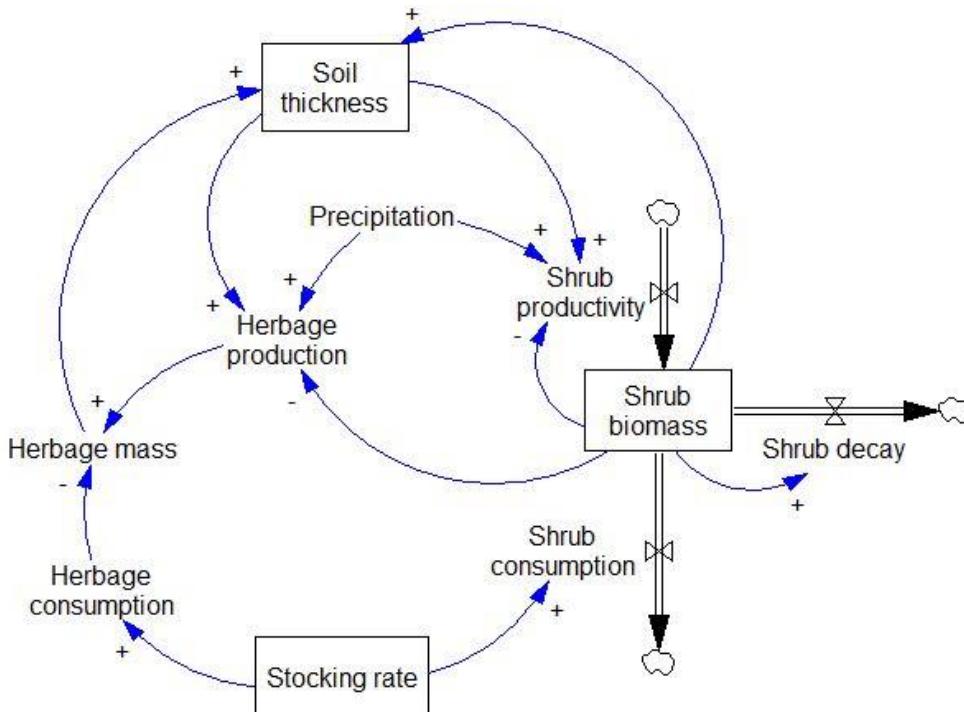
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Shrubs – grass competition.

As mentioned above, the degradation of grazing areas in the Mediterranean has two opposing causes. DESPAS considers the most common, i.e., that overgrazing removes vegetation cover and triggers erosion rates. However, the excess of woody vegetation at the expense of pasture resulting from undergrazing is not sustainable either, since it does not allow livestock activity (in this sense, degradation is considered as a loss of economic productivity). In both cases, the resulting degradation is difficult to reverse. On the one hand, the global average rate of soil formation is 0.036 mm per year [71], so that recovering 1 cm of soil takes 278 years. On the other hand, once perennial plants are able to establish, they have an inherent advantage over annual plants at the beginning of the growing season. Since the latter have to restart their growth cycle from seed, they lose the competition for nutrients and light to established perennials, which emerge quickly from dormancy at the end of winter or a dry season [72].

We included the interaction between annual and perennial species (Fig. 5) to enrich the behaviour possibilities of the model and simulate shrub encroachment, which takes places in abandoned European rangelands [73]. For this purpose, herb productivity depends on shrub biomass through a multiplier. It considers that, in the absence of woody species, herb productivity is maximum (depending on rainfall and soil thickness), while as the proportion of woody species increases, annual herb productivity decreases until it is cancelled out when woody plants have colonized all the available space. It was assumed that both annual and

306 perennial herbs dry out at the end of the growing season (end of spring) and start growing again
the next season (autumn) from seeds, roots or underground stems. Since only aboveground
biomass is considered and the time scale of the model is annual, no stock variable is needed for
herbs, as they are annual plants.



309

Figure 5. Sketch diagram for the interaction between woody and herbaceous vegetation.

312 *Supplementary feeding*

313 In commercial rangelands, one of the common strategies for coping with resource scarcity
during dry seasons or droughts is the use of supplementary feeding. Sometimes, in addition,
315 another drought-enduring strategy comes into play, such as allowing animals to lose weight
during these shortages. Our model, however, assumes that all the energy requirements of the
318 animals are always met and for this purpose there is a sub-model dedicated to calculating the
amount of supplementary feed required and its cost.

321 Although the use of animal feed began as a temporary practice, it has been consolidated
as a common practice that allows increasing the stocking rate. The basic structure of this sub-
324 model is as follows (Fig. 6): The energy gap resulting from the lack of pasture due to (i) the
excessive presence of animals, (ii) drought periods, or (iii) reduced soil fertility due to erosion,
increases the need for supplementary feeding. This has a negative impact on the benefit of the
farmer, which should lead to a reduction in the stocking density. Relieving pressure on pasture
327 leads to its recovery, which brings the situation back to the starting point, i.e. the animals would
return to grazing exclusively on pasture and feed costs would disappear. However, fluctuations
in feed prices can play an important role and allow for high stocking rates under scenarios of

soil and pasture degradation. This sub-model presents one of the ways in which the scarcity signals of the territory are bypassed by the use of external inputs.

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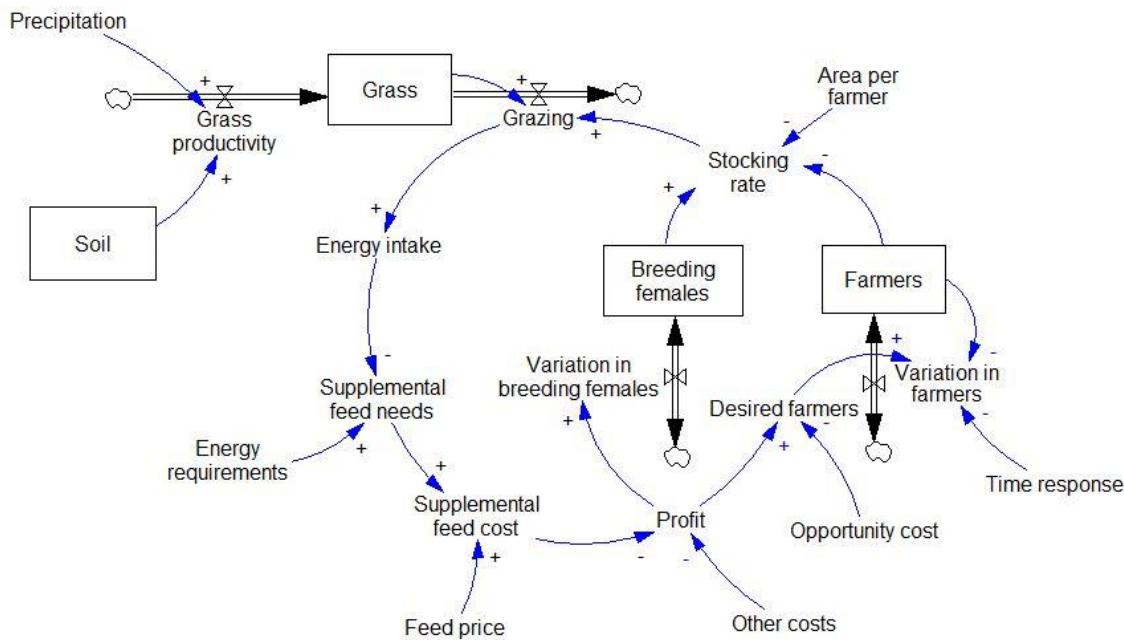


Figure 6. Sketch diagram for supplementary feed dynamics and goal seeking behavior for the variation of farmers in the modelled area.

333

Farmers' behavior.

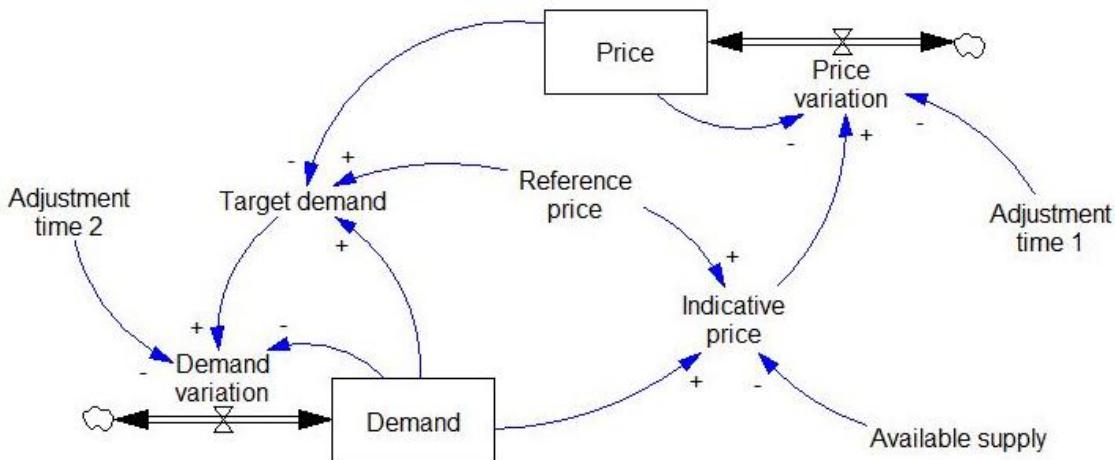
336 One of the main assumptions of the GDM model is that consumption units (U) –the number of livestock farmers present in the area–, depends on the profitability in relation to the opportunity cost, i.e., the alternative profit that would be obtained in another economic sector. To implement 339 this hypothesis, the classical model of “goal-seeking” behaviuor [50] is used. The discrepancy between current number of farmers (a stock variable) and the desired ones (the target in the 342 goal-seeking model) is eliminated after a time delay by a positive or negative flow, depending on the sign of the discrepancy (note that this discrepancy is also dynamic, as the target changes) (Fig. 6). Desired farmers depend on the profitability-opportunity cost ratio. The former variable is a function, in turn, of income and costs, which are built up from prices, subsidies, sales and 345 purchase volumes, which include the supplementary food item. The opportunity cost, on the other hand, can have a constant value or be a stochastic variable that follows an exponential probability distribution, i.e., the greater the opportunity cost, the less likely it is. This reflects 348 well the fact that there are more economic actors with low opportunity costs, i.e., with alternative economic activities that offer a lower economic return than their current activity. The adjustment time of the function makes it possible to reflect the behaviour of the economic 351 agents involved. It can be more opportunistic (shorter delays) or conservative (longer delays).

354 *Price forming mechanism.*

In the initial versions of DESPAS model, prices of inputs and outputs of the modelled goods are considered as exogenous variables. However, this approach is not very realistic, since the price of raw materials is subject to changes derived from various circumstances, such as the current energy crisis. In addition, the internal dynamics of the system itself is responsible for changes in the prices of the products generated. Depending on the size of the livestock sector in the modeled area, the input and output market may be more or less influenced.

The price formation mechanism is similar for all commodities considered and it is represented in Figure 7. The sub-model assumes that farmers and traders lack complete knowledge of the system, so they use the hill-climbing heuristic to adjust their expectations to reality; i.e., the prices prevailing in the model at each instant are determined by the level variable “Price”. A reference price (which may be global or regional) and a price derived from the interplay of supply and demand are involved in the “Indicative price” setting. The product in question (feed, meat...) evolves towards this price with a certain delay (“Adjustment time 1”).

The price, in turn, determines the “Target demand”, towards which the demand converges with another lag, the “Adjustment Time 2”. As demand changes, the indicative prices change, and so does the price. This simple structure is capable of generating a great complexity of behavior and, above all, eliminates the simplicity of considering that prices are fixed for the entire simulation period.



375 **Figure 7.** Sketch diagram for the price formation mechanism. The sub-model is based on the
“goal-seeking” behavior algorithm. The “target” variable for price dynamics is the Indicative
price, which depends on three variables: a reference price, product demand and available
378 supply.

Temporal and spatial scales.

381 Classical models of ecology do not refer to any specific spatial scale [74]. Our approach is, in
this sense, more strict, since the developed models refer to a spatial unit [52], such as hectare,
but do not distinguish between different parts within that space. The models presented in this
384 section uses superimpose two-time scales - short and medium term - to detail processes
operating at different resolutions. First, the day is used to model the evolution of soil water,
considering variables such as infiltration, saturation, runoff and evapotranspiration. For purely
387 operational reasons, the time unit is not exactly 1 day. The implementation of the models in the
Vensim[©] software [75] makes it necessary to use time units (when the time unit is the year) that
are a multiple of 2.85 days (≈ 0.0078125 years), as this is the minimum time step allowed by the
390 program.

393 The year is used to represent processes occurring in the medium term, such as the
evolution of the livestock population or the number of economic agents operating in the
territory or their profits. Finally, the simulation periods cover several years, tens or even
centuries, since their purpose is to prospect the sustainability of the system, i.e., its long-term
396 stability. For this purpose, it is necessary to study the behavior of variables whose dynamics are
much slower (e.g., soil thickness, pasture productivity) and whose effect is felt over several
decades.

399 **4. Design and implementation of analysis tools to explore rangelands behavior.**

402 In this section we review the procedures we have designed and applied to analyze the modeled
social-ecological systems. The exploitation of a model ranges from running a simple simulation
scenarios, which is the default use of a SD model, to the implementation of thousands of
405 scenarios to rank the factors involved in a model. (Fig. 8). As these analyses become more
sophisticated, programming routines are needed to automate the process of scenario creation
and import, model simulation and data export [76].

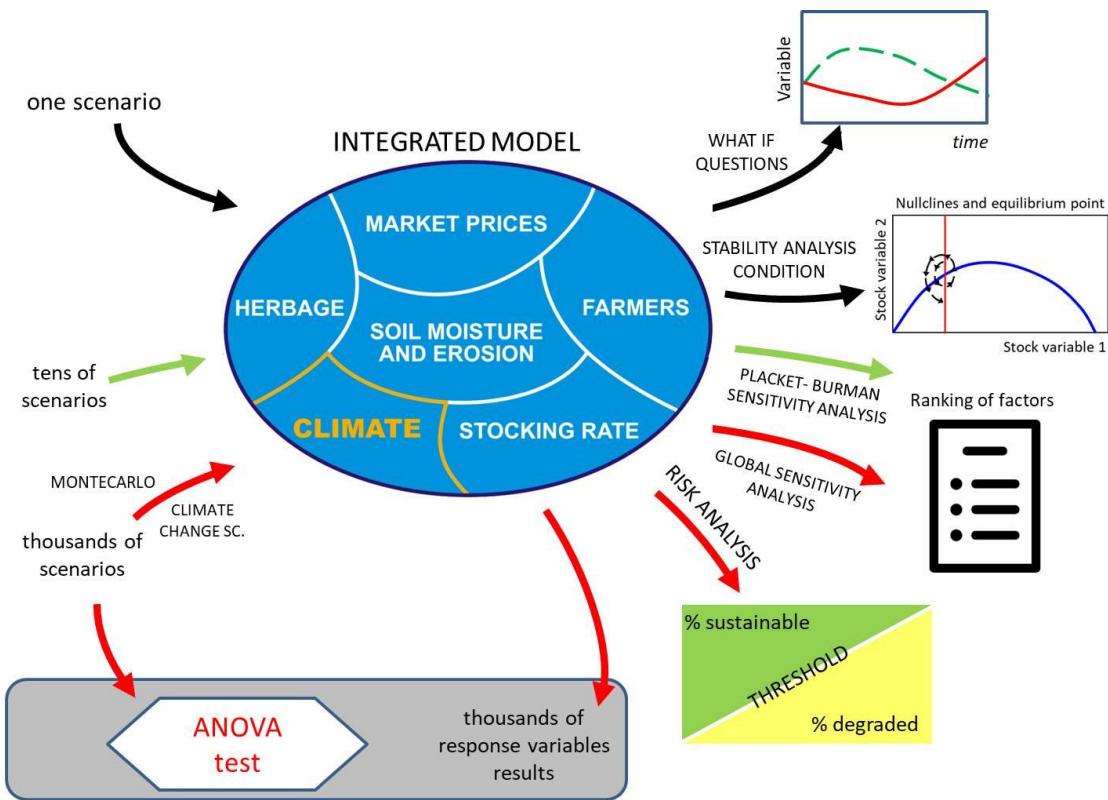


Figure 8. Different options for using SD models, ranging from the simulation of one scenario to

408 the implementation of thousands of scenarios required for a Global Sensitivity Analysis.

4.1. Temporal trends and “what if” questions.

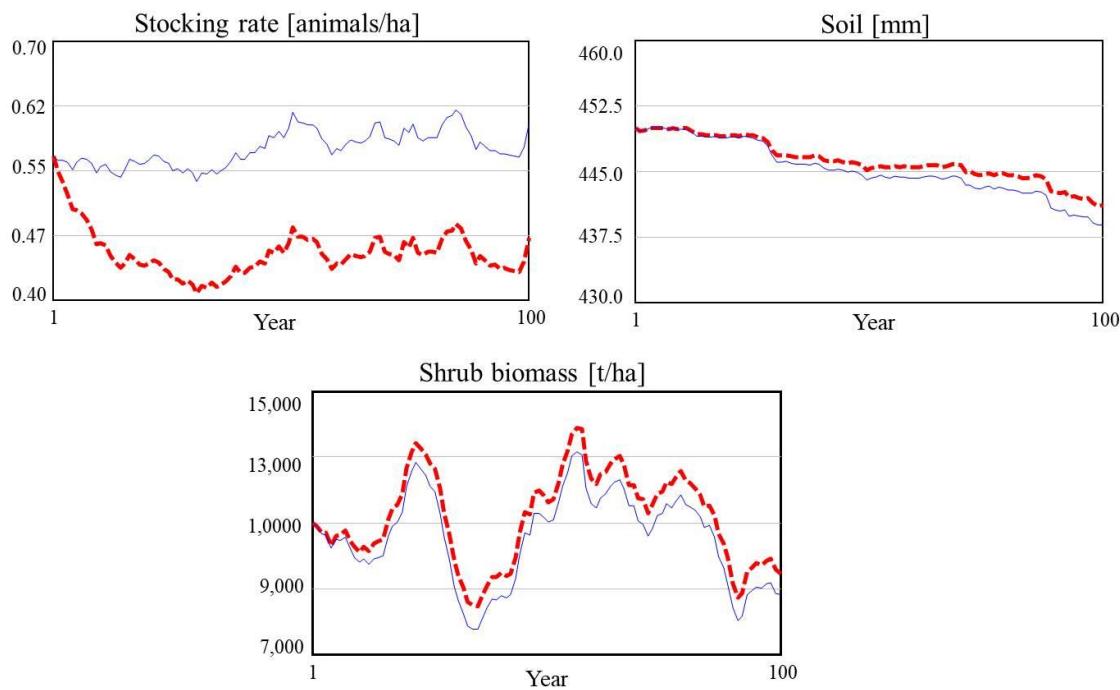
411 The standard output of SD models are time trends of their variables (Fig. 9). They respond to
 412 the scenario of simulation, i.e., the values of parameters and exogenous variables. Strictly
 413 speaking, these trajectories should not be considered as predictions, since the background of the
 414 equations used is of a socio-ecological nature, i.e., they do not respond to laws of a physical and
 415 universal nature. Models that are founded on economic, social and even biological formulations
 416 try to explore the future, but cannot forecast what will happen [77].

417 In this context it is extremely useful to compare different scenarios, i.e., to answering
 418 'what if' questions to analyze deviations from the baseline scenario. The following example
 419 (Fig. 9) shows what would happen if subsidies were halved in Lagadas rangelands (Greece)
 420 [73]. As can be seen, the stocking density is falling as the financial support is reduced (although
 421 not to the same extent), easing the pressure on the environment and slowing down erosion rates.
 422 In the absence of grazing, grasslands are invaded by woody species, which helps to protect the
 423 soil but at the same time reduces the productive capacity of grasslands.

424 Following the line of this exercise, it was interesting to look for the level of subsidy
 425 with which the erosion would be cancelled. This would require a reduction in subsidies of up to
 426 60%, which would mean a 26% drop in livestock (values not found in the historical record of
 427 the area) and a 30% decrease in the gross margin. According to this simulation results it seems

that erosion is inherent in grazing and that limiting soil erosion may in practice mean that

429 farmers will have to close down their business.



432 **Figure 9.** Time trends for three variables in Lagadas under two scenarios (default, blue solid line; and half subsidies, dotted red line).

435 4.2. Stability analysis condition.

In order to gain a more precise idea of the long-term sustainability of grazing systems, it is possible to develop procedures that give us a more global vision than the more or less random 438 simulation of scenarios. For this aim, the study of the stability of dynamic systems through the qualitative analysis of their equations [54,78] is the appropriate path to follow. Due to the uncertainty that is usually associated with the parametric values of many systems, and in 441 particular those referring to the natural environment [79–81], the qualitative analysis of a model can often be of greater interest than its quantitative results [82].

444 This methodological approach has been applied to dynamic predator-prey systems through the analysis of nullclines, both in linear [83] and non-linear [84] models and, more 447 specifically, to ecological [85] and grazing systems [57,86]. A nullcline is defined as the equilibrium of a level equation (N), i.e., the equation resulting from performing $dN/dt=0$. With them it is possible to anticipate the behavior of a system in the long term by knowing the parametric values of the scenario and the initial values of the stock variables. This gives an idea of where the system is heading under current conditions, which serves as an early warning 450 indicator.

Figure 10 shows the phase plane Pasture–Stocking rate, its nullclines and the equilibrium point associated to its intersection. The stability of the equilibrium depends on the slope of the Pasture nullcline at the point of cut [86]. In this case, since the slope is positive, we are facing a stable equilibrium. To illustrate the use of these indicators, we used parametric scenarios to recreate three standard extensive livestock farming systems in Spain: cattle and sheep farmed on the dehesas and goats farmed on the south-eastern pastures [87,88].

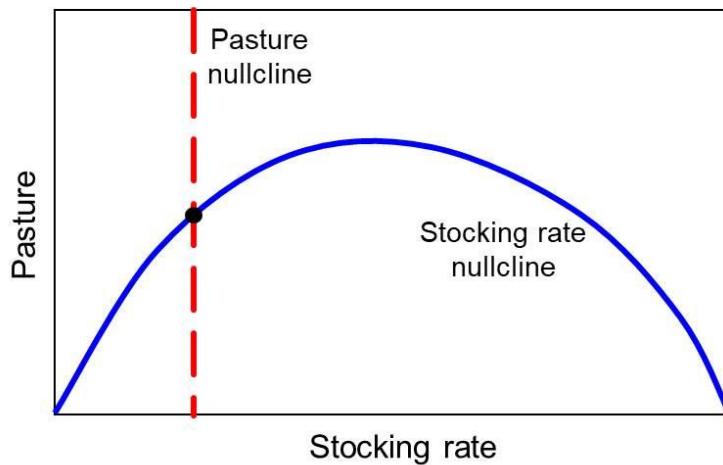


Figure 10. Nullclines and long-term equilibrium point for the subsystem Pasture-Stocking rate. The equilibrium point represent the values of pasture and stocking-rate at which the system will stabilize.

462

4.3 Risk analysis.

The use of nullclines and graphical qualitative analysis is limited by the complexity of the model. Although it is possible to visualize three-dimensional isoclines [88,89], when the SD model has more than three level variables or the formulation of some nonlinear equation is intricate, it is not possible to obtain the nullclines equations. In this case, long-term equilibria are obtained by simulating the model with time horizons long enough to ensure the stabilization of the values. In addition, calculating the nullclines of a system means 'freezing' a scenario and assuming that everything will remain the same in the future. However, conditions fluctuate permanently

To get a more precise idea of where the system is going, further equilibrium points can be calculated by varying the baseline scenario. These scenarios can be randomly generated using the Monte Carlo method by converting some model parameters into stochastic variables. For example, instead of using the mean precipitation, random values can be extracted from a stochastic variable that considers the mean and variance of precipitation. The procedure results in clouds of equilibrium points represented in a scatter plot (Fig. 11). The dispersion of the cloud is critical to have a diagnosis. When it is high (Fig. 11A), the system's time-trajectory will

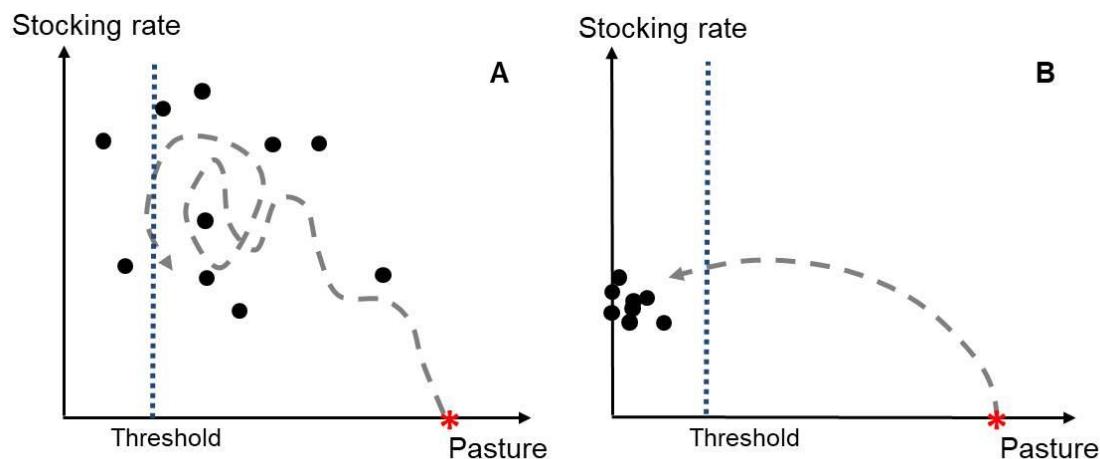
480 wander rather erratically; if dispersion is low (Fig. 11B), the time-trajectory will be more predictable.

483 To determine the risk of degradation, it is necessary to add degradation thresholds. Our role as modelers has often been to put these tools in the hands of specialists so that they can establish the thresholds they consider appropriate as well as other parametric values of the models. Additionally, to enrich the estimation of risks, it is evaluated the time needed to reach the defined thresholds. Bear in mind that a model could show a desertification risk of 100%, but if it occurs after thousands of years (remember that the model simulates the time needed to reach a stable equilibrium), the risk may be negligible. To implement this idea the model includes equations for computing the time the variables take to exceed their degradation thresholds. In this way, a probability of desertification will be obtained together with a "time to desertification" whose average will provide an estimate in each case.

486

492 The application of this methodology allowed to estimate the risk of desertification for the five "desertification landscapes" [22,76,90], included in the Spanish Action Plan against Desertification (SAPD; MAGRAMA, 2008). The results tell us that dehesas, are one of the most sustainable land uses. Neither the soil nor the vegetation had an appreciable risk of deterioration 495 over a 100-year time horizon, while for other desertification landscapes, such as groundwater-dependent irrigation systems, the results says that the risk of desertification is 88.2%, ant that it will take, on average, 47 years.

498



501 **Figure 11.** Cloud of long-term equilibriums for the Stocking Rate-Pasture subsystem. In some instances, the clustering of points clearly points towards a region of the scatterplot (B), while in others the dispersion of the point cloud will not provide a clear forecast (A). The most likely path followed by the system from its original situation (red asterisk) is the one indicated by the 504 dotted line. In the first case a clearer trajectory (dashed line) can be expected, while in the

second case the dispersion of points predicts an erratic trajectory. Note the threshold (dotted line) separating the degradation region form the sustainable

507

4.4. Ranking of factors.

One of the objectives of the models presented is to have a precise idea of the most important factors in the future of the system. Specifically, and within the framework of desertification, it is crucial to distinguish between anthropic and climatic causes [91]. The Plackett-Burman Sensitivity Analysis (PBSA) [92,93] is an excellent option for ranking the factors of a socio-ecological system. This is a sound statistical procedure that measures the effects of each parameter on the target variables in an efficient way in terms of the number of necessary scenarios. An important feature is that the effects of every parameter are not measured with the all-other-things-being-equal assumption but are averaged over variations made in all other parameters. PBSA also enables measuring two-way interactions of pairs of parameters, although this option has not been used in this case.

519 Fortunately, the analysis capacity of computers is no longer an excuse to simulate a large number of scenarios. This paves the way to implement much more robust and conclusive sensitive analysis, such as Global Sensitivity Analysis (GSA) [94,95]. The most common 522 GSAs are variance-based methods, which decompose the variance of a target variable into terms corresponding to the different parameters and their interactions [96].

525 Among the main conclusions reached through the establishment of rankings, we have been able to verify the supremacy of climatic factors over the rest. In our latest works [97,98] it is clear, at least for the case of the pastures, that the main cause of degradation is related to 528 climate factors. For example, when the “Mean annual precipitation” is increased by 10%, the time for the soil to be depleted was brought forward by 36.9%, while the effect for economic and behavioural variables were located in the lowest positions in the ranking. For example, a 10% increase in “Mean meat price” delays time for the soil to be depleted by -1.2%. The 531 explanation for this result is strongly influenced by supplementary feeding, a common practice in commercial rangelands. Although this is one of the major costs of livestock farms, the farmer has enough financial margin to invest in feed and thus maintain production and, therefore, 534 profit. Obviously, this situation may change if or when the prices of raw materials used to manufacture compound feed.

537 4.5. Implementation of ANOVA test.

SD models can be used as virtual laboratories in which to conduct experiments [99]. In this context a multi-way ANOVA test was coupled to a SD model to evaluate the sensitivity of a 540 valuable type of commercial rangelands to increases in the frequency and intensity of droughts

543 considering climate change scenarios [100]. In particular, the question is whether the current strategy of using feed to mitigate the effects of droughts will continue to be effective in the context of water scarcity that is expected to be particularly relevant in the Mediterranean [16].

546 For this purpose, 5400 simulation scenarios have been generated from two blocking factors and two treatment factors. We have considered three Representative Concentration Pathway (RCP), i.e. scenario of future greenhouse gas emissions, and two downscaling method, i.e. process by which coarse-resolution Global Climate Models outputs are translated into local climate information. Additionally, three levels were defined for the frequency and intensity of 549 droughts. A hundred simulations (replicates) were run for each of the $3 \cdot 2 \cdot 3 \cdot 3 = 54$ cells in the analysis. These were obtained by varying the value of the random seed from 1 to 100.

552 The scenarios feed the model to generate results and after those inputs and outputs are used to implement the multi-way ANOVA test (see Fig 8. bottom). This has shown that most of the main effects and interactions turned out to be highly significant although sensitivity of 555 response variables to increases in the frequency and severity of droughts under climate change would be low or very low.

5. Findings through SD modelling.

558 5.1. Learnings from Mediterranean rangelands modeling.

561 Agro-silvo-pastoral systems are one of the five desertification landscapes identified in the SAPD [21]. Our main conclusion in this context is that this land use presents a low risk of 564 desertification [22,90]. This is due to the use of feed, that allows mitigating the scarcity of precipitation, it is estimated that the system will cope well with the shortage of pasture with the use of feed. Consistent with this conclusion, sensitivity analyses have revealed that climatic factors are more decisive than socio-economic factors [70]. This reinforces the validity of the 567 use of feed as a drought-enduring strategy that safeguards the system.

570 However, we cannot think that the use of animal feed is a panacea. In northern Algeria we have an example of how the progressive replacement of grass with cereal grain has led to the 573 system's collapse [101–103]. In these steppe rangelands, feed initially entered, as is often the case, as a punctual solution for extreme drought situations. Gradually, it became a regular supplement until national policies decided to turn the so-called Alfa seas (the name indicates the density of bushes in the region; Alfa is the name for the esparto grass, *Macrochloa tenacissima*) into an open-air farm. To this end, barley gradually replaced the country's wheat fields. Through a state policy of subsidies, this barley is used to feed the increasingly numerous herds of the steppes. The main mistake was to ignore the sheep's fibre needs, as barley only met their energy 576 requirements. The consequences were devastating: thousands of hungry animals devoured the esparto grass, which was the shrub that helped alleviate periods of grass shortage. In South of

579 Oran 700,000 ha out of 1.2 Mha of Alfa grass has completely disappeared and the remaining
half million is much sparser (biomass was reduced from 1,750 kg DM ha⁻¹ to 100 kg DM ha⁻¹)
[104]. The loss of plant cover combined with the strong winds in the area have led to the
appearance of dunes. This is a good example to illustrate that desertification is not the advance
582 of a desert, but the creation of a desert-like landscape due to poor land management [105].

585 The livestock industry, which revolves around the use of compound feed, is a good
example of global telecoupling [106], i.e. global supply chains involving large geographical
distances and creating environmental pressures (including deforestation and other types of land
conversions) remote from the places where the consumption of goods and services take place.
Although industrial farming is the main consumer of feed, a more comprehensive assessment of
588 the environmental impact of extensive farming may include the area of soybeans and cereal
fields needed to supplement the animals' diet. In the European case, the deforestation of primary
forests in South America due to soy imports for feed compound is especially relevant [107]. For
591 the period 2000-2010 we have estimated that soybean consumption associated with the Spanish
feed industry is equivalent to the deforestation of 1,220 kha of primary ecosystems in South
America, the main exporter of soybeans [108]. The models we have presented can be completed
594 by incorporating the impact of feed consumption on the livestock farms studied in terms of area
deforested.

597 Although socioeconomic drivers have less influence than climate drivers on the
sustainability of the rangelands, there are many situations where their role is key. In Lagadas
(Greece) we observed how the reduction of subsidies triggered the deterioration of the system
[73]. Something similar to the Algerian case described above occurred. The rangeland scientists
600 who helped us with that model expected that the cut in subsidies would lead to a reduction in
livestock and thus slow down erosion. However, the model showed the opposite behavior. The
conclusion seemed obvious to our colleagues: the model had to be wrong. Analyzing in depth
603 the reasons for such unexpected behavior, we saw that what was happening was that the
livestock, although it was decreasing, did not do so in the proportion in which the subsidies did.
Analyzing the causal tree we could see that the reduction of subsidies meant a reduction of
606 supplementary feeding but not to the same extent of the stocking rate. Consequently, the actual
stocking rate was higher than in the baseline scenario, and therefore the animals were forced to
consume more grass than was adequate, since the feed given was not sufficient to cover their
609 needs.

612 Another relevant dynamic of degradation of the Mediterranean grazing systems has to
do with the economic behavior of farmers [109]. We have seen that a few opportunistic farmers,
who only seek to maximize their profit by playing with the size of the herds, are enough to
trigger degradation rates in the environment. The more cautious behavior of traditional farmers
is only effective, in terms of rangeland sustainability, when it is highly dominant.

615

5.2. Multidisciplinarity: under the crossfire of specialists.

The scientific literature is full of recommendations about the need for multidisciplinary studies
618 as the only way to address a multi-faceted and increasingly interconnected reality. Specifically,
economics, combined with earth system sciences, is crucial for understanding both positive and
621 negative impacts of alternatives and the trade-offs involved in a sustainable development path
[110]. This is especially relevant to the serious environmental problems facing the planet, such
624 as global warming, desertification or loss of biodiversity. A more harmonious relationship
between food systems and the ecological framework on which they are based is called for in
627 order to achieve the Sustainable Development Goals [111]. As a result of this demand,
numerous journals specialized in the multidisciplinary have emerged, and initiatives such as the
EAT-Lancet [112] that bet on the systemic approach are launched. New paradigms have also
627 emerged such as the socio-ecological systems [113], ecological economics [42] or the water-
food-energy nexus [114], which try to give an integrated vision of nature and human beings.

Our experience during all these years has shown us that the integration of knowledge
630 from different disciplines is difficult, to say the least. Inevitably, multidisciplinary work is
evaluated by specialists in each of the subjects that are included in the integrated models. The
633 problem is that, for a specialist, nothing is superfluous in his field and she/he declares
she/himself incapable of judging and appreciating the added value of the contributions of other
disciplines, which she/he does not know. Thus, for example, we find that an edaphologist
636 misses in the erosion sub-model, much more detailed equations, pointing out the impossibility
of using point models, instead of spatially explicit ones, or considers unacceptable the
simplification that involves ignoring the lithological characteristics of the terrain. However, it
will be difficult to appreciate that this same model contains equations on the evolution of prices
639 according to changes between supply and demand. Likewise, an economist will miss a more in-
depth treatment of the profit and loss account, and a botanist may criticize the fact that the
dynamics of each of the species that make up the pasture have not been treated separately. For
642 both the economist and the botanist, it is likely to be superfluous to model runoff in order to
calculate erosion rates.

Another practice that we have observed and that seriously penalizes the construction of
645 integrated models is the growing refusal to review this type of work. Again, at least part of the
explanation lies in the fact that the review work is carried out by specialists in the different
disciplines that the model brings together, but who are not usually familiar with equations,
648 much less with systems of differential equations. This task requires a great deal of time for
understanding, as well as a minimum of mathematical knowledge. We are faced with judgments
that again do not go beyond the boundaries of the reviewer's discipline. At best the reviewer
651 assumes that a model with so many equations and references must be right (with all the

654 vagueness that this judgment implies), at worst the paper runs the risk of being rejected outright if the reviewer in question reads some detail that clashes with his or her perception of the subject.

657 In our case, we have had work rejected on the basis of arguments that demonstrate a lack of knowledge of the model. It has been said that the model is speculative (indeed it is, as is the case with any model based on a series of hypotheses or speculations), that the time horizons are excessive (in some cases it is necessary to simulate the model for several hundred years in order to calculate equilibrium points of the system), that it is too simple (in models with more 660 than eighty equations) or that the model is wrong because it does not reflect reality. In this last aspect we agree since, in the end, "All models are wrong", since they are deliberate simplifications of reality [115]. From our point of view, this type of judgment fits in perfectly 663 with one of the obstacles Sterman points to in properly understanding complex dynamic systems [50]: unscientific reasoning, even among the scientific community itself.

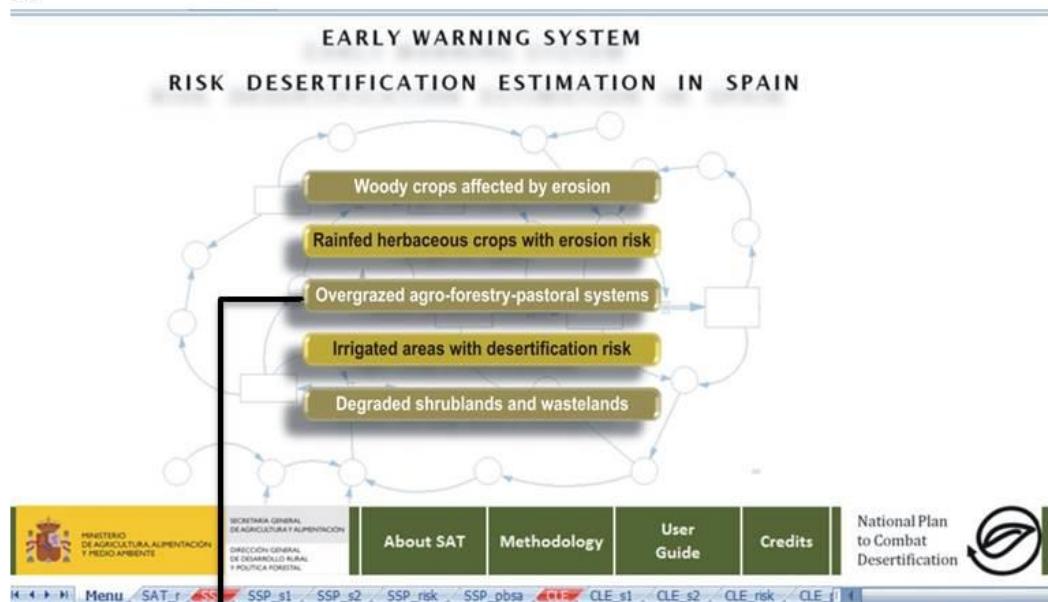
666 There are notable exceptions to this discourse. For example, there are those who appreciate the connection of aspects as far apart, in principle, as subsidies and erosion rates. This is the culmination of the top-down approach of the systemic approach models. Indeed, one 669 of the major achievements is to complete the model, in the sense of connecting all the elements of the system. It is obvious that these connections can be made more precise and improved over years. The important thing is to make the assumptions very clear and to return to these questions whenever possible and pertinent. On the contrary, the bottom-up approach, which is the 672 immediate consequence of the reductionist approach of the scientific method, tries to aggregate particles of knowledge in such a way that a complex system is generated from the coupling of subsystems. As a consequence, its predictive capacity is quite high. However, this approach has 675 a number of disadvantages [116] that are critical for our objectives: (i) They are models that need a large amount of data for their operation; which, in arid areas, is often not possible; (ii) There is a great risk of error propagation; and (iii) The strategy of trying to capture and replicate 678 all kinds of processes makes bottom-up models hardly reach 'the top'.

681 Over the years, we have found a number of specialists in fields such as hydrology, ecology, geography or biology who have joined our working group and become enthusiastic advocates of the systemic approach. We must also acknowledge and thank the valuable 684 contributions of reviewers from outside SD, which have allowed us to improve both models and manuscripts. One of the tools that are useful for involving participants from different disciplines and institutions are Decision Support Systems (DSS). These are very simple computer applications in which the user only has to press a series of buttons to execute tasks such as moving from one screen to another or performing more or less complex calculations. In our 687 case, the DSS's allow us to use Vensim © [117] through Visual Basic. This open the door to use

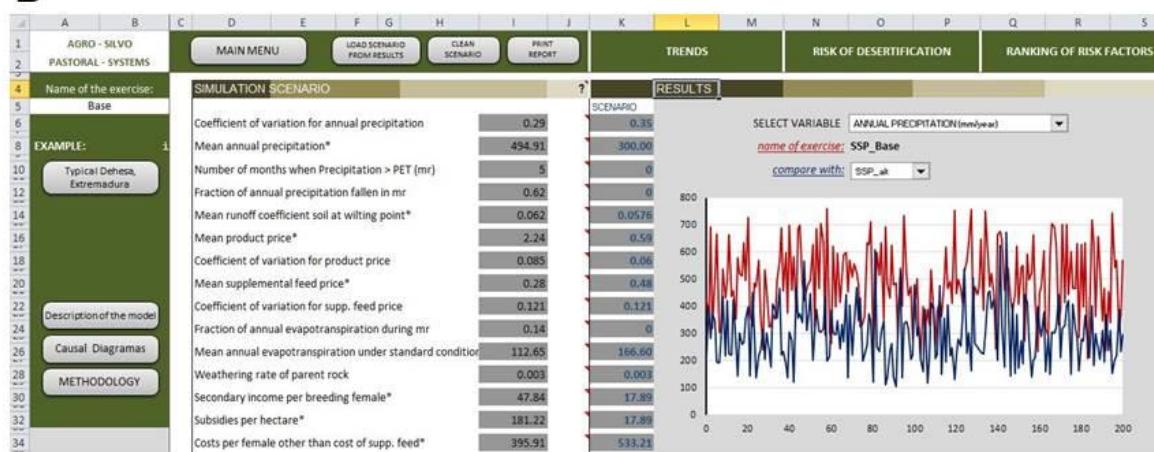
a widely spread program such as Excel and to simulate SD models remotely, so that both scenarios and results are accessible from a spreadsheet.

690 DSS can play a key role in expanding the scientific production to society, since it allows exploring in a simple way sophisticated simulation models and their results, involving the decision making processes [118] and reducing the resistance that many times produces facing
693 environmental problems such as desertification [119]. Many of the methods developed during these fifteen years have been channeled into a DSS called SAT (the Spanish acronym for Early Warning System) [22,76,90]. SAT implements three SD models to cope with the five
696 desertification landscapes described in the SPAD, two of which are related to the “rangelands affected by erosion” syndrome (Fig. 12B). Despite their usefulness, we agree with Oxley (2004) [120] on the limited role of DSS and simulation models and that “decision-support for socio-
699 natural systems is more fruitfully concerned with providing the political actors involved a means of exploration than a set of ‘definite’ solutions” [120].

A



B



702

Figure 12. SAT screens: (A) Main menu; (B) Implementation of SAT for Dehesa rangelands, one of the Spanish NAPD landscapes.

705

6. Conclusions

Simulation models are a vital tool for understanding the multiple dynamics that converge on rangelands. This is the main land use in drylands and is key to the survival of the poorest countries. Over the course of two decades, we have developed integrated SD models to study Mediterranean rangelands and designed analytical tools coupled to them. Our goal was to understand the interactions between the different components of the system, to provide sustainability indicators and to detect the main drivers of degradation of these socio-ecological systems.

Since the beginning of our research activity, we have addressed the study of rangelands from a holistic approach. Although multidisciplinarity in the study of socio-ecological systems

is repeatedly advised, in many cases the specialist's point of view and reluctance to integrate
717 knowledge from other disciplines still prevails. This is one of the burdens that the modeler must
learn to bear, distinguishing constructive criticisms from those that only arise from those who
refuse to leave their discipline of comfort and do not admit other points of view.

720 As we work on models, we encounter new challenges that call for new developments,
which has led us to versions that incorporate new elements. Currently, two situations are of
particular concern to us. On the one hand, transformation of rangelands and silvo-pastoral
723 dryland systems to croplands increases the risk of desertification due to increased pressure on
the remaining rangelands or to the use of unsustainable cultivation practices. To address this
726 problem it is necessary to include other land use dynamics and one option is to link them with
other models we have implemented for other land uses, such as groundwater dependent
irrigation systems. On the other hand, we have to take into account the effects that move beyond
729 the physical boundaries of rangelands due to feed consumption. These are some of the possible
paths that models will follow. At the same time, new models usually require different analytical
tools, which we have also been developing over the years.

732 In an increasingly complex world, it is mandatory to use tools that can deal with it.
Simply pointing out the contradictions that arise in land use management and bringing them to
the attention of stakeholders and politicians is, in our opinion, a valuable contribution.

735 Acknowledgements

738 The authors are indebted to numerous research projects, thanks to which they have enjoyed the
necessary conditions to develop the studies cited in this work. We dare to cite here those that
specifically address rangelands: DeSurvey (CE-Integrated Project Contract No. 003950),
PADEG (CGL2008/01215/BTE) and BIODESERT (European Research Council grant
agreement n° 647038).

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References

- 744 1. Menke, J.; Bradford, G.E. Rangelands. *Agric. Ecosyst. Environ.* **1992**, *42*, 217–230.
2. Cherlet, M.; Hutchinson, C.; Reynolds, J.; Hill, J.; Sommer, S.; von Maltitz, G. *World
Atlas of Desertification*; Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S.,
747 von Maltitz, G., Eds.; Publication Office of the European Union: Luxembourg, 2018;
ISBN 978-92-79-75350-3.
3. Lund, G. Accounting for the World's Rangelands. *BioOne* **2007**, *29*, 3–10.
- 750 4. Bedunah, D.J.; Angerer, J.P. Rangeland Degradation, Poverty, and Conflict: How Can
Rangeland Scientists Contribute to Effective Responses and Solutions? *Rangel. Ecol.
Manag.* **2012**, *65*, 606–612, doi:10.2111/REM-D-11-00155.1.

753 5. Asner, G.P.; Elmore, A.J.; Olander, L.P.; Martin, R.E.; Harris, A.T. Grazing Systems, Ecosystem Responses, and Global Change. *Annu. Rev. Environ. Resour.* **2004**, *29*, 261–299, doi:10.1146/annurev.energy.29.062403.102142.

756 6. Maestre, F.T.; Bagousse-pinguet, Y. Le; Delgado-Baquerizo, M.; Eldridge, D.J.; Saiz, H.; Berdugo, M.; Gozalo, B.; Ochoa, V.; Guirado, E. Grazing and Ecosystem Service Delivery in Global Drylands. *Science (80-)* **2022**, *1*–7.

759 7. Maestre, F.T.; Eldridge, D.J.; Soliveres, S.; Sonia, K.; Delgado-baquerizo, M.; Bowker, M.A.; Garc, P.; Gait, J.; Gallardo, A.; Roberto, L. Structure and Functioning of Dryland Ecosystems in a Changing Structure and Functioning of Dryland Ecosystems in a Changing World. *Annu. Rev. Ecol. Evol. Syst.* **2016**, *47*, 215–237, doi:10.1146/annurev-ecolsys-121415-032311.

762 8. Reynolds, J.F.; Smith, D.M.S.; Lambin, E.F.; Turner II, B.L.; Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B., E.F.; Turner II, B.L.; Mortimore, M.; Batterbury, S.P.J.; Downing, T.E.; Dowlatabadi, H.; et al. Global Desertification: Building a Science for Dryland Development. *Science (80-)* **2007**, *316*, 847–851, doi:10.1126/science.1131634.

768 9. Allington, G.R.H.; Li, W.; Brown, D.G. Modeling System Dynamics in Rangelands of the Mongolian Plateau. In Proceedings of the Proceedings of the Trans-disciplinary Research Conference: Building Resilience of Mongolian Rangelands; Ulaanbaatar, Mongolia, 2015; pp. 216–221.

774 10. Fu, Q.; Feng, S. Responses of Terrestrial Aridity to Global Warming. *J. Geophys. Res. Atmos.* **2014**, *119*, 7863–7875, doi:10.1002/2014JD021608.

777 11. Huang, J.; Yu, H.; Guan, X.; Wang, G.; Guo, R. Accelerated Dryland Expansion under Climate Change. *Nat. Clim. Chang.* **2015**, *6*, 166–172, doi:10.1038/NCLIMATE2837.

780 12. Lin, L.; Gettelman, A.; Fu, Q.; Xu, Y. Simulated Differences in 21st Century Aridity Due to Different Scenarios of Greenhouse Gases and Aerosols. *Clim. Change* **2018**, *146*, 407–422, doi:10.1007/s10584-016-1615-3.

783 13. Park, C.-E.; Jeong, S.-J.; Joshi, M.; Osborn, T.J.; Ho, C.-H.; Piao, S.; Chen, D.; Liu, J.; Yang, H.; Park, H.; et al. Keeping Global Warming within 1.5 °C Constrains Emergence of Aridification. *Nat. Clim. Chang.* **2018**, *8*, 70–74, doi:10.1038/s41558-017-0034-4.

786 14. Le Houérou, H.N. Impact of Man and His Animals on Mediterranean Vegetation. In *Mediterranean-type shrublands, Ecosystems of the World 11*; Castri, F., Goodall, D., Specht, R., Eds.; Elsevier Science Publishers Co.: New York, NY, 1981; pp. 479–521.

789 15. Samaniego, L.; Thober, S.; Kumar, R.; Wanders, N.; Rakovec, O.; Pan, M.; Zink, M.; Sheffield, J.; Wood, E.F.; Marx, A. Anthropogenic Warming Exacerbates European Soil Moisture Droughts. *Nat. Clim. Chang.* **2018**, *8*, 421–426, doi:10.1038/s41558-018-0138-

5.

16. Cramer, W.; Guiot, J.; Fader, M.; Garrabou, J.; Gattuso, J.P.; Iglesias, A.; Lange, M.A.;
792 Lionello, P.; Llasat, M.C.; Paz, S.; et al. Climate Change and Interconnected Risks to
Sustainable Development in the Mediterranean. *Nat. Clim. Chang.* **2018**, *8*, 972–980,
doi:10.1038/s41558-018-0299-2.

795 17. Papanastasis, V.; Mansat, P. *Grasslands and Related Forage Resources in
Mediterranean Areas*; 1996; Vol. 1;.

798 18. UN (United Nations) *United Nations Convention to Combat Desertification in Countries
Experiencing Serious Drought and/or Desertification, Particularly in Africa. Document
A/AC. 241/27, 12. 09. 1994 with Annex*; New York, 1994;

801 19. Mensching, H.G. Desertification in Europe ? A Critical Comment With Examples From
Mediterranean Europe. In *Desertification in Europe*; Fantechi, R., Margaris, N.S., Eds.;
Springer: Dordrecht, 1986; pp. 3–8.

804 20. European Court of Auditors *Combating Desertification in the EU: A Growing Threat in
Need of More Action.*; Brussels, Belgium, 2018;

807 21. MAGRAMA *Programa de Acción Nacional Contra La Desertificación. Madrid*;
Ministerio de Agricultura y Medio Ambiente: Madrid, Spain, 2008;

810 22. Martínez-Valderrama, J.; Ibáñez, J.; Del Barrio, G.; Sanjuán, M.E.; Alcalá, F.J.;
Martínez-Vicente, S.; Ruiz, A.; Puigdefábregas, J. Present and Future of Desertification
in Spain: Implementation of a Surveillance System to Prevent Land Degradation. *Sci.
Total Environ.* **2016**, *563–564*, 169–178, doi:10.1016/j.scitotenv.2016.04.065.

813 23. MITERD Estrategia Nacional de Lucha Contra La Desertificación En España. **2022**,
159.

816 24. Martínez-Valderrama, J.; del Barrio, G.; Sanjuán, M.E.; Guirado, E.; Maestre, F.T.
Desertification in Spain: A Sound Diagnosis without Solutions and New Scenarios. *Land*
2022, *11*, 272, doi:https://doi.org/10.3390/land11020272.

819 25. Manzano, P.; Burgas, D.; Cadahía, L.; Eronen, J.T.; Fernández-Llamazares, Á.;
Bencherif, S.; Holand, Ø.; Seitsonen, O.; Byambaa, B.; Fortelius, M.; et al. Toward a
Holistic Understanding of Pastoralism. *One Earth* **2021**, *4*, 651–665,
doi:10.1016/j.oneear.2021.04.012.

822 26. Ayoub, A.T. Extent, Severity and Causative Factors of Land Degradation in the Sudan.
J. Arid Environ. **1998**, *38*, 397–409, doi:https://doi.org/10.1006/jare.1997.0346.

825 27. Schnabel, S. *Soil Erosion and Runoff Production in a Small Watershed under Silvo-
Pastoral Landuse (Dehesas) in Extremadura, Spain*; Geoforma Ediciones: Logroño,
Spain, 1997;

28. Teketay, D. *Deforestation, Wood Famine, and Environmental Degradation in Ethiopia's
Highland Ecosystems: Urgent Need for Action*; 2001; Vol. 8;.

29. Wilcox, B.P.; Thurow, T.L. Emerging Issues in Rangeland Ecohydrology: Vegetation
828 Change and the Water Cycle. *Rangel. Ecol. Manag.* **2006**, *59*, 220–224.

30. Perevolotsky, A.; Seligman, N.G. Role of Grazing in Mediterranean Rangeland
Ecosystems - Inversion of a Paradigm. *Bioscience* **1998**, *48*, 1007–1017.

831 31. Moreira, F.; Rego, F.C.; Ferreira, P.G. Temporal (1958–1995) Pattern of Change in a
Cultural Landscape of Northwestern Portugal: Implications for Fire Occurrence. *Landsc.
Ecol.* **2001**, *16*, 557–567, doi:10.1023/A:1013130528470.

834 32. Puigdefábregas, J. Erosión y Desertificación En España. *Campo* **1995**, *132*, 63–83.

33. MedECC *Risks Associated to Climate and Environmental Changes in the Mediterranean
Region*; 2019;

837 34. Ruffault, J.; Moron, V.; Trigo, R.M.; Curt, T. Objective Identification of Multiple Large
Fire Climatologies: An Application to a Mediterranean Ecosystem. *Environ. Res. Lett.*
2016, *11*, 7.

840 35. Turco, M.; Llasat, M.C.; von Hardenberg, J. Provenzale, A. Climate Change Impacts on
Wildfires in a Mediterranean Environment. *Clim. Change* **2014**, *125*, 369–380.

36. Syphard, A.; Radeloff, V.; Hawbaker, T.; Stewart, S. Conservation Threats Due to
843 Human-Caused Increases in Fire Frequency in Mediterranean-Climate Ecosystems.
Conserv. Biol. **2009**, *23*, 758–769, doi:10.1111/j.1523-1739.2009.01223.x.

37. Zedler, P.H.; Gautier, C.R.; McMaster, G.S. Vegetation Change in Response to Extreme
846 Events: The Effect of a Short Interval between Fires in California Chaparral and Coastal
Scrub. *Ecology* **1983**, *64*, 809–818.

38. Canadell, J.; López-Soria, L. Lignotuber Reserves Support Regrowth Following
849 Clipping of Two Mediterranean Shrubs. *Func. Ecol.* **1998**, *12*, 31–38.

39. Arianoutsou, M.; Vilà, M. Fire and Invasive Plant Species in the Mediterranean Basin.
Isr. J. Ecol. Evol. **2012**, *58*, 195–203, doi:10.1560/IJEE.58.2-3.195.

852 40. Gea-Izquierdo, G.; Cañellas, I.; Montero, G. Acorn Production in Spanish Holm Oak
Woodlands. *Investig. Agrar. For. Syst.* **2006**, *13*, 339–354, doi:10.5424/srf/2006153-
00976.

855 41. Liu, J.; Mooney, H.; Hull, V.; Davis, S.J.; Gaskell, J.; Hertel, T.; Lubchenco, J.; Seto,
K.C.; Gleick, P.; Kremen, C.; et al. Systems Integration for Global Sustainability.
Science (80-.). **2015**, *347*, doi:10.1126/science.1258832.

858 42. Costanza, R. Ecological Economics: Reintegrating the Study of Humans and Nature.
Ecol. Appl. **1996**, *6*, 978–990, doi:10.2307/2269581.

43. Engler, J.O.; von Wehrden, H. Global Assessment of the Non-Equilibrium Theory of
861 Rangelands: Revisited and Refined. *Land use policy* **2018**, *70*, 479–484,
doi:10.1016/j.landusepol.2017.11.026.

44. Maestre, F.T.; Salguero-Gómez, R.; Quero, J.L. It Is Getting Hotter in Here:

864 Determining and Projecting the Impacts of Global Environmental Change on Drylands.
Philos. Trans. R. Soc. B Biol. Sci. **2012**, *367*, 3062–3075, doi:10.1098/rstb.2011.0323.

45. Stafford Smith, D.M.; McKeon, G.M.; Watson, I.W.; Henry, B.K.; Stone, G.S.; Hall, W.B.; Howden, S.M. Learning from Episodes of Degradation and Recovery in Variable 867 Australian Rangelands. *Proc. Natl. Acad. Sci.* **2007**, *104*, 20690–20695.

46. Reynolds, J.F.; Stafford Smith, M. Do Humans Cause Deserts? In *Global 870 Desertification. Do Human Cause Deserts*; Reynolds, J., Stafford Smith, M., Eds.; Dahlem University Press, 2002; pp. 1–21.

47. Vetter, S. Rangelands at Equilibrium and Non-Equilibrium: Recent Developments in the 873 Debate. *J. Arid Environ.* **2005**, *62*, 321–341.

48. Liu, J.; Dietz, T.; Carpenter, S.R.; Alberti, M.; Folke, C.; Moran, E.; Pell, A.N.; Deadman, P.; Kratz, T.; Lubchenco, J.; et al. Complexity of Coupled Human and Natural 876 Systems. *Science (80-)* **2007**, *317*, 1513–1516, doi:10.1126/science.1144004.

49. Forrester, J.W. *Industrial Dynamics*; The MIT Press: Cambridge, 1961;

50. Sterman, J.D. *Business Dynamics: Systems Thinking and Modeling for a Complex 879 World*; Mc Graw Hill, 2000; ISBN 0-07-231135-5.

51. Davies, E.G.R.; Simonovic, S.P. Global Water Resources Modeling with an Integrated Model of the Social-Economic-Environmental System. *Adv. Water Resour.* **2011**, *34*, 684–700, doi:10.1016/j.advwatres.2011.02.010.

52. Kelly, R.A.; Jakeman, A.J.; Barreteau, O.; Borsuk, M.E.; ElSawah, S.; Hamilton, S.H.; Henriksen, H.J.; Kuikka, S.; Maier, H.R.; Rizzoli, A.E.; et al. Selecting among Five 882 Common Modelling Approaches for Integrated Environmental Assessment and Management. *Environ. Model. Softw.* **2013**, *47*, 159–181, doi:10.1016/j.envsoft.2013.05.005.

53. MEA (Millenium Ecosystem Assessment) *Ecosystems and Human Well-Being: 888 Desertification Synthesis.*; World Resources Institute: Washington, DC., 2005;

54. Aracil, J. *Introducción a La Dinámica de Sistemas*; Alianza Editorial: Madrid, 1986;

55. Lotka, A.J. *Elements of Mathematical Biology*; Dover Publications: New York, 1956;

56. Volterra, V. Variations and Fluctuations of the Number of Individuals in Animal Species 891 Living Together. In *Animal Ecology*; Chapman, B.M., Ed.; McGraw-Hill: New York, 1931; pp. 409–448.

57. Noy-Meir, I. Stability of Grazing Systems: An Application of Predator-Prey Graphs. *J. Ecol.* **1975**, *63*, 459–481, doi:10.2307/2258730.

58. Noy-Meir, I. Grazing and Production in Seasonal Pastures: Analysis of a Simple Model. *J. Appl. Ecol.* **1978**, *15*, 809–835, doi:10.2307/2402778.

59. Thornes, J.B. The Ecology of Erosion. *Geography* **1985**, *70*, 222–235.

60. Thornes, J.B. Erosional Equilibria under Grazing. In Proceedings of the Conceptual 900

issues in environmental archaeology; Bintliff, J.L., Davidson, D.A., Grant, E.G., Eds.; Edinburgh University Press: Edinburgh, 1988.

903 61. Ibáñez, J.; Martínez-Valderrama, J.; Puigdefábregas, J. Assessing Desertification Risk Using System Stability Condition Analysis. *Ecol. Modell.* **2008**, *213*, 180–190, doi:10.1016/j.ecolmodel.2007.11.017.

906 62. Ibáñez, J.; Martínez-Valderrama, J.; Schnabel, S. Desertification Due to Overgrazing in a Dynamic Commercial Livestock-Grass-Soil System. *Ecol. Modell.* **2007**, *205*, 277–288, doi:10.1016/j.ecolmodel.2007.02.024.

909 63. Martínez-Valderrama, J.; Ibáñez, J. Foundations for a Dynamic Model to Analyze Stability in Commercial Grazing Systems. In *Sustainability of Agrosilvopastoral Systems – Dehesas, Montados-*; Schnabel, S., Ferreira, A., Eds.; Advances in Geoeology, 2004; pp. 173–182 ISBN 3-923381-50-6.

912 64. Holling, C.S. The Components of Predation as Revealed by a Study of Small-Mammal Predation of the European Pine Sawfly. *Can. Entomol.* **1959**, *91*, 293–320, doi:DOI: 10.4039/Ent91293-5.

915 65. Band, L.E. Field Parameterization of an Empirical Sheetwash Transport Equation. *Catena* **1985**, *12*, 201–210.

918 66. Kirkby, M.J. Soil Development Models as a Component of Slope Models. *Earth Surf. Process.* **1977**, *2*, 203–230, doi:https://doi.org/10.1002/esp.3290020212.

921 67. Thornes, J.B. The Interaction of Erosional and Vegetational Dynamics in Land Degradation: Spatial Outcomes. In *Vegetation and erosion*; Thornes, J.B., Ed.; John Wiley & Sons: Chichester, 1990; pp. 41–53.

924 68. Elwell, H.A.; Stocking, M. Vegetal Cover to Estimate Soil Erosion Hazard in Rhodesia. *Geoderma* **1976**, *15*, 61–70, doi:10.1016/0016-7061(76)90071-9.

927 69. Ibáñez, J.; Lavado Contador, J.F.; Schnabel, S.; Pulido Fernández, M.; Martínez-Valderrama, J. A Model-Based Integrated Assessment of Land Degradation by Water Erosion in a Valuable Spanish Rangeland. *Environ. Model. Softw.* **2014**, *55*, 201–213, doi:10.1016/j.envsoft.2014.01.026.

930 70. Ibáñez, J.; Lavado Contador, J.F.; Schnabel, S.; Martínez-Valderrama, J. Evaluating the Influence of Physical, Economic and Managerial Factors on Sheet Erosion in Rangelands of SW Spain by Performing a Sensitivity Analysis on an Integrated Dynamic Model. *Sci. Total Environ.* **2016**, *544*, 439–449, doi:10.1016/j.scitotenv.2015.11.128.

933 71. Montgomery, D.R. Soil Erosion and Agricultural Sustainability. *Proc. Natl. Acad. Sci. U. S. A.* **2007**, *104*, 13268–13272, doi:10.1073/pnas.0611508104.

936 72. Tilman, D. *Resource Competition and Community Structure*.; Princeton University Press: New Jersey, 1982;

73. Ibáñez, J.; Martínez-Valderrama, J.; Papanastasis, V.; Evangelou, C.; Puigdefábregas, J.

A Multidisciplinary Model for Assessing Degradation in Mediterranean Rangelands. *L. Degrad. Dev.* **2014**, *25*, 468–482, doi:10.1002/lde.2165.

939 74. Atanasova, N.; Džeroski, S.; Kompare, B.; Todorovski, L.; Gal, G. Automated
Discovery of a Model for Dinoflagellate Dynamics. *Environ. Model. Softw.* **2011**, *26*,
942 658–668, doi:<https://doi.org/10.1016/j.envsoft.2010.11.003>.

75. Ventana Systems Inc. VensimDSS Software 2006.

942 76. Martínez-Valderrama, J.; Ibáñez, J.; Alcalá, F.J.; Martínez, S. SAT: A Software for
945 Assessing the Risk of Desertification in Spain. *Sci. Program.* **2020**, *2020*, 7563928,
doi:10.1155/2020/7563928.

948 77. Perry, G.L.W.; Millington, J.D.A. Spatial Modelling of Succession-Disturbance
Dynamics in Forest Ecosystems: Concepts and Examples. *Perspect. Plant Ecol. Evol.*
Syst. **2008**, *9*, 191–210.

951 78. May, R.M. Thresholds and Breakpoints in Ecosystems with a Multiplicity of Stable
States. *Nature* **1977**, *269*, 471–477.

954 79. Frank, P.M. *Introduction to System Sensitivity Theory*; Academic Press: New York,
1978; ISBN 978-0122656507.

957 80. Swart, J. *Sensitivity of a Hyrax-Lynx Mathematical Model to Parameter Uncertainty*;
1987; Vol. 83;.

81. van Coller, L. Automated Techniques for the Qualitative Analysis of Ecological Models:
Continuous Models. *Conserv. Ecol.* **1997**, *1*, 5.

82. Martínez-Vicente, S.; Requena, A. *Dinámica de Sistemas. 1. Simulación Por Ordenador*;
Alianza Editorial: Madrid, Spain., 1986;

960 83. Rosenzweig, M.L.; MacArthur, R.H. Graphical Representation and Stability Conditions
of Predator-Prey Interactions. *Am. Nat.* **1963**, *97*, 209–223.

84. Edelstein-Keshet, L. *Mathematical Models in Biology*; The Random House: New York,
963 1988;

85. Holling, C.S. *Resilience and Stability of Ecological Systems*; 1973; Vol. 4;.

86. Gotelli, N.J. *A Primer in Ecology*; 2nd ed.; Sinauer Associates Inc. Publishers:
966 Massachussets, 1998;

87. Ibáñez, J.; Martínez, J.; Schnabel, S. Desertification Due to Overgrazing in a Dynamic
Commercial Livestock-Grass-Soil System. *Ecol. Modell.* **2007**, *205*, 277–288,
969 doi:10.1016/j.ecolmodel.2007.02.024.

88. Martínez-Valderrama, J. Análisis de La Desertificación Por Sobrepastoreo Mediante Un
Modelo de Simulación Dinámico, Universidad Politécnica de Madrid, 2006.

972 89. Ibáñez, J.; Martínez-Valderrama, J.; Schnabel, S. Desertification Due to Overgrazing in a
Dynamic Commercial Livestock-Grass-Soil System. *Ecol. Modell.* **2007**, *205*, 277–288,
doi:10.1016/j.ecolmodel.2007.02.024.

975 90. Ibáñez, J.; Martínez-Valderrama, J.; Martínez Vicente, S.; Martínez Ruiz, A.; Rojo Serrano, L. *Procedimientos de Alerta Temprana y Estimación de Riesgos de Desertificación Mediante Modelos de Dinámica de Sistemas*; Ministerio de Agricultura, 978 Alimentación y Medio Ambiente: Madrid, 2015; ISBN 978-84-491-0074-1.

981 91. Xu, D.; Li, C.; Zhuang, D.; Pan, J. Assessment of the Relative Role of Climate Change and Human Activities in Desertification: A Review. *J. Geogr. Sci.* **2011**, *21*, 926–936, doi:10.1007/s11442-011-0890-1.

984 92. Plackett, R.L.; Burman, J.P. The Design of Optimum Multifactorial Experiments. *Biometrika* **1946**, *33*, 305–325, doi:10.2307/2332195.

987 93. Beres, D.L.; Hawkins, D.M. Plackett–Burman Technique for Sensitivity Analysis of Many-Parametered Models. *Ecol. Modell.* **2001**, *141*, 171–183, doi:https://doi.org/10.1016/S0304-3800(01)00271-X.

990 94. Gan, Y.; Duan, Q.; Gong, W.; Tong, C.; Sun, Y.; Chu, W.; Ye, A.; Miao, C.; Di, Z. A Comprehensive Evaluation of Various Sensitivity Analysis Methods: A Case Study with a Hydrological Model. *Environ. Model. Softw.* **2014**, *51*, 269–285, doi:10.1016/J.ENVSOFT.2013.09.031.

993 95. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M. *Global Sensitivity Analysis: The Primer*; John Wiley & Sons: Chichester, 2008;

996 96. Sobol, I.M. Global Sensitivity Indices for Nonlinear Mathematical Models and Their Monte Carlo Estimates. *Math. Comput. Simul.* **2001**, *55*, 271–280, doi:https://dx.doi.org/10.1016/S0378-4754(00)00270-6.

999 97. Ibáñez, J.; Martínez-Valderrama, J.; Contador, J.F.L.; Fernández, M.P. Exploring the Economic, Social and Environmental Prospects for Commercial Natural Annual Grasslands by Performing a Sensitivity Analysis on a Multidisciplinary Integrated Model. *Sci. Total Environ.* **2020**, *705*, 135860, doi:10.1016/j.scitotenv.2019.135860.

1002 98. Martínez-Valderrama, J.; Ibáñez, J.; Alcalá, F.; Sanjuán, M.E.; Ruiz, A.; Del Barrio, G. Estimating Rangelands Vulnerability to Droughts under the Threat of an Increasing Climate Uncertainty. *Agric. Syst.* **2019**, *In press*.

1005 99. Potkonjak, V.; Gardner, M.; Callaghan, V.; Mattila, P.; Guel, C.; Petrović, V.M.; Jovanović, K. Virtual Laboratories for Education in Science, Technology, and Engineering: A Review. *Comput. Educ.* **2016**, *95*, 309–327, doi:https://doi.org/10.1016/j.compedu.2016.02.002.

1008 100. Martínez-Valderrama, J.; Ibáñez, J.; Ibáñez, M.A.; Alcalá, F.J.; Sanjuán, M.E.; Ruiz, A.; del Barrio, G. Assessing the Sensitivity of a Mediterranean Commercial Rangeland to Droughts under Climate Change Scenarios by Means of a Multidisciplinary Integrated Model. *Agric. Syst.* **2021**, *187*, 103021, doi:10.1016/j.agrsy.2020.103021.

1011 101. Martínez-Valderrama, J.; Ibáñez, J.; Del Barrio, G.; Alcalá, F.J.; Sanjuán, M.E.; Ruiz,

A.; Hirche, A.; Puigdefábregas, J. Doomed to Collapse: Why Algerian Steppe Rangelands Are Overgrazed and Some Lessons to Help Land-Use Transitions. *Sci. Total Environ.* **2018**, *613–614*, 1489–1497, doi:10.1016/j.scitotenv.2017.07.058.

1014 102. Hirche, A.; Salamani, M.; Abdellaoui, A.; Benhouhou, S.; Martínez-Valderrama, J. Landscape Changes of Desertification in Arid Areas: The Case of South-West Algeria. *Environ. Monit. Assess.* **2011**, *179*, 403–420.

1017 103. Slimani, H.; Aidoud, A. Desertification in the Maghreb: A Case Study of an Algerian High-Plain Steppe. In *Environmental Challenges in the Mediterranean 2000-2050*; Marquina, A., Ed.; Kluwer Academic Publishers, 2004; pp. 93–108.

1020 104. Aidoud, A. Vegetation Changes and Land Use Changes in Algerian Steppe Rangelands. In *Restauración de la cubierta vegetal en ecosistemas mediterráneos*; Pastor-López, A., Seva-Román, E., Eds.; Instituto de Cultura Juan-Gil Albert: Alicante, 2002; pp. 53–80.

1023 105. Martínez-Valderrama, J.; Guirado, E.; Maestre, F.T. Unraveling Misunderstandings about Desertification: The Paradoxical Case of the Tabernas-Sorbas Basin in Southeast Spain. *Land* **2020**, *9*, 269, doi:10.3390/land9080269.

1026 106. Yu, Y.; Feng, K.; Hubacek, K. Tele-Connecting Local Consumption to Global Land Use. *Glob. Environ. Chang.* **2013**, *23*, 1178–1186, doi:10.1016/j.gloenvcha.2013.04.006.

1029 107. WWF (World Wildlife Fund) *The Growth of Soy: Impacts and Solutions.*; Gland, Switzerland, 2014;

1032 108. Martínez-Valderrama, J.; Sanjuán, M.E.; Barrio, G.; Guirado, E.; Ruiz, A.; Maestre, F.T. Mediterranean Landscape Re-Greening at the Expense of South American Agricultural Expansion. *Land* **2021**, *10*, 204, doi:10.3390/land10020204.

1035 109. Ibáñez, J.; Martínez-Valderrama, J. Global Effectiveness of Group Decision-Making Strategies in Coping with Forage and Price Variabilities in Commercial Rangelands: A Modelling Assessment. *J. Environ. Manage.* **2018**, *217*, 531–541, doi:10.1016/j.jenvman.2018.03.127.

1038 110. Polasky, S.; Kling, C.L.; Levin, S.A.; Carpenter, S.R.; Daily, G.C.; Ehrlich, P.R.; Heal, G.M.; Lubchenco, J. Role of Economics in Analyzing the Environment and Sustainable Development. *Proc. Natl. Acad. Sci. U. S. A.* **2019**, *116*, 5233–5238, doi:10.1073/pnas.1901616116.

1041 111. Herrero, M.; Thornton, P.K.; Mason-D'Croz, D.; Palmer, J.; Bodirsky, B.L.; Pradhan, P.; Barrett, C.D.; Benton, T.G.; Hall, A.; Pikaar, I.; et al. Articulating the Impact of Food Systems Innovation on the Sustainable Development Goals. *Lancet Planet. Heal.* **2020**, *5* 196, 1–13, doi:10.1016/S2542-5196(20)30277-1.

1044 112. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A.; et al. Food in the Anthropocene: The EAT–Lancet Commission on Healthy Diets from Sustainable Food

Systems. *Lancet* **2019**, *393*, 447–492, doi:10.1016/S0140-6736(18)31788-4.

1050 113. Berkes, F.; Folke, C. *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience.*; Berkes, F., Folke, C., Ed.; Cambridge University Press: Cambridge, 1998;

1053 114. Ringler, C.; Bhaduri, A.; Lawford, R. The Nexus across Water, Energy, Land and Food (WELF): Potential for Improved Resource Use Efficiency? *Curr. Opin. Environ. Sustain.* **2013**, *5*, 617–624, doi:<https://doi.org/10.1016/j.cosust.2013.11.002>.

1056 115. Sterman, J. All Models Are Wrong: Reflections on Becoming a Systems Scientist. *Syst. Dyn. Rev.* **2002**, *18*, 501–531, doi:10.1002/sdr.261.

116. Wang, E.; Zhang, L.; Cresswell, H.; Hickel, K. *Comparison of Top-Down and Bottom-Up Models for Simulation of Water Balance as Affected by Seasonality, Vegetation Type and Spatial Land Use*; 2006;

1059 117. Ventana Systems Inc. VensimDSS 2019.

1062 118. van Delden, H.; Seppelt, R.; White, R.; Jakeman, A.J. A Methodology for the Design and Development of Integrated Models for Policy Support. *Environ. Model. Softw.* **2011**, *26*, 266–279, doi:<http://dx.doi.org/10.1016/j.envsoft.2010.03.021>.

1065 119. D’Odorico, P.; Bhattachan, A.; Davis, K.; Ravi, S.; Runyan, C. Global Desertification: Drivers and Feedbacks. *Adv. Water Resour.* **2013**, *51*, 326–344, doi:10.1016/j.advwatres.2012.01.013.

1068 120. Oxley, T.; McIntosh, B.S.; Winder, N.; Mulligan, M.; Engelen, G. Integrated Modelling and Decision-Support Tools: A Mediterranean Example. *Environ. Model. Softw.* **2004**, *19*, 999–1010, doi:10.1016/j.envsoft.2003.11.003.

1071 121. Davis, D.K. *The Arid Lands. History, Power, Knowledge*; The MIT Press: Cambridge, MA, 2016;

122. Swearingen, W.D. Agricultural Reform in North Africa: Economic Necessity and Environmental Dilemmas. In *North Africa : development and reform in a changing global economy*; Vandewalle, D.J., Ed.; St. Martin’s Press: New York, 1996; pp. 67–92.

1074 123. Martínez-Valderrama, J.; Ibañez, J.; Alcalá, F.J.; Dominguez, A.; Yassin, M.;

1077 Puigdefábregas, J. The Use of a Hydrological-Economic Model to Assess Sustainability in Groundwater-Dependent Agriculture in Drylands. *J. Hydrol.* **2011**, *402*, 80–91, doi:10.1016/j.jhydrol.2011.03.003.

1080