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Research article

# Environmental strategies increase the resilience of extensive livestock systems to adverse climate conditions

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ABSTRACT

This study presents an agent-based model to assess the resilience and ecological, economic, and social sustainability of three extensive livestock system archetypes: *subsistence*, *commercial*, and *environmental*. *Subsistence* focuses on traditional practices, *commercial* prioritizes profit, and *environmental* emphasizes resource conservation and animal welfare. The model simulates livestock dynamics under two grazing strategies (free and rotational grazing) under thirty climate-driven primary productivity change scenarios as a proxy to explore the potential long-term and persistent impacts of climate change. Results indicate that all archetypes reach a collapse threshold under extreme climate conditions, and that no single strategy performs best under all circumstances. The *environmental* performs best under adverse but non-critical conditions, especially in ecological sustainability; the *subsistence* is the most vulnerable and the *commercial* excels in economic and social sustainability under favorable conditions. Under normal or favorable climate-driven conditions, tradeoffs between sustainability dimensions emerge. Rotational grazing improves ecological sustainability, but reduces economic and social performance. Strategies to reduce tradeoffs are essential to improve the ecological footprint of commercial systems and the economic viability of environmental systems under changing climates. This model has the potential to be transferable and adaptable to a wide range of extensive livestock systems, providing a valuable tool for research and policy aimed at building climate-resilient pastoral systems.

## 1. Introduction

Extensive livestock systems are crucial to human wellbeing and regional food security, as they are the main source of livelihood for about 500 million people worldwide (Mbow et al., 2019) and occupy approximately 30 % of the Earth's land surface (Howell et al., 2019; Soumya et al., 2022). Defined as systems that rely primarily on natural resources with minimal external inputs and centered on grazing, they are typically characterized by the use of locally adapted livestock species and breeds, as well as the use of diverse pastures in response to their spatial and temporal availability (Ruiz-Mirazo et al., 2017). Climate change poses a serious threat to these livestock systems due to their dependence on local natural resources and climate conditions (Aydinalp and Cresser, 2008; Uddin and Kebreab, 2020). These systems are also responsible for significant environmental and social challenges, including overgrazing, soil degradation, water pollution, greenhouse gas emissions, and biodiversity loss (Herrero et al., 2013; Springmann et al., 2018). Thus, understanding not only the potential impact of climate change on the resilience and long-term sustainability of extensive livestock systems but also their environmental impacts is of critical importance.

Climate change affects extensive livestock systems both directly and indirectly. Rising temperatures and changing precipitation patterns, and more frequent extreme weather events (e.g., droughts, floods, wildfires)

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increase heat stress, alter water and forage availability and quality, and disrupts pests and diseases dynamics (Rojas-Downing et al., 2017). These changes negatively affect livestock health and mortality (Megersa et al., 2014; Faisal et al., 2021), productivity (Nardone et al., 2010), and mobility (Freier et al., 2014; Turner et al., 2016). Climate change also drives socio-economic disruptions such as resource conflicts, migration pressures and market instability, further undermining the resilience of pastoralist communities (Turner et al., 2011; FAO, 2021). Despite experimental studies (Dumont et al., 2015; Dellar et al., 2018), there is significant uncertainty about the long-term climate change impacts on primary productivity (Felton et al., 2022). The diversity, complexity, and uncertainty of climate change impacts on extensive livestock systems highlight the need for approaches that comprehensively address these challenges to assess their resilience and sustainability.

Extensive livestock systems are complex social-ecological systems where social, economic, ecological, and institutional factors interact across multiple scales (Berkes and Folke, 1998; Moraine et al., 2016; Ruggia et al., 2021). Their resilience to climate change and long-term sustainability depends on these interactions. Resilience refers to a system's ability to resist disturbances, adapt to changes, and, if necessary, transform to endure emerging challenges (Walker et al., 2004; Walker, 2020). In this study, we use resistance to disturbances as a proxy for resilience. Sustainability entails maintaining economic viability and social wellbeing while ensuring the renewal of natural resources (Ruggerio, 2021). Given the complexity of these systems, tradeoffs often arise between the social, economic and ecological dimensions of sustainability (Accatino et al., 2019; Austrheim et al., 2016). Moreover, interactions between resilience and sustainability may emerge from the tensions between persistence and change within the system (Grafton et al., 2019). Agent-based models (ABM) are a valuable tool for exploring these interactions, offering insights into long-term responses to climate change and the emergence of synergies and tradeoffs.

ABM integrate biophysical, social, and social-ecological interactions (Bitterman and Bennett, 2018; Janssen and Ostrom, 2006; Thober et al., 2017) and adopt a bottom-up approach, allowing system-level outcomes emerge from individual actions rather than being predefined by deterministic equations (Grimm, 1999; Janssen, 2020). Previous studies have used ABM to simulate the dynamics of extensive livestock systems under climate change. Dieguez Cameroni et al. (2012, 2014) explored the interactions between farmer management decisions and climate variability, highlighting the importance of adaptive management in preventing system collapse. Jakoby et al. (2015) used an ecological-economic rangeland model to assess adaptive grazing strategies under climate variability and space heterogeneity, emphasizing the need of adapting grazing practices to seasonal and spatial conditions. Martin et al. (2014, 2016) built spatially explicit social-ecological models of pastoral systems in Morocco to assess household economic vulnerability to climate variability and droughts. Dressler et al. (2019) examined how changes in household behavior, such as abandonment of grazing norms or income diversification, affect the long-term resilience of pastoral common property systems. Overall, these studies provide valuable insights into the vulnerability of extensive livestock systems and adaptive management. However, most focus on one or two sustainability dimensions, with social factors being the least explored and potential tradeoffs largely overlooked. Furthermore, they address short-term impacts of climate variability or drought, without considering potential long-term and persistent impacts on primary productivity.

In this study, using an ABM approach, we provide a systematic analysis of the potential long-term and persistent impacts of climate change on primary productivity in extensive livestock systems. We assess its effects on resilience and social, economic, and ecological sustainability, while also examining the tradeoffs that emerge among these dimensions. Given the wide range of extensive livestock systems, we model the behavior of three representative archetypes: *subsistence*, *commercial* and *environmental*. Our results provide critical insights into the management strategies that could most effectively strengthen livestock systems against climate-related challenges, even under extreme conditions.

## 2. Methods

We built the ABM SOSLIVESTOCK to explore the long-term effects of climate change on three archetypes of extensive livestock systems, through its impact on primary productivity. We assessed their resilience and sustainability under two grazing management strategies (free grazing and rotational grazing) across a wide gradient of climate-driven productivity changes. The archetypes are described below, followed by an overview of the decision-making process in the model. The model is available in Soler-Navarro et al. (2024), and a detailed description is provided in Supplementary Material 1. SOSLIVESTOCK was implemented in NetLogo v.6.3.3 (Wilensky, 1999).

### *2.1. Archetypes of extensive livestock systems*

We modeled three archetypes of extensive livestock systems, referred to here as *subsistence*, *commercial*, and e*nvironmental* (Table 1), which represent the diverse range of livestock management practices worldwide. We relied on empirical evidence found in the literature, expert knowledge, and interviews with livestock farmers from five arid and semi-arid regions (Tenza-Peral et al., 2017, 2019, 2022; Perez-Ibarra et al., 2023) to support the definition and management strategies of the three archetypes (Table 1). See Supplementary Material 2 for a description of the case studies and their alignment with the three archetypes. Supplementary Material 3 includes the surveys used to interview farmers and experts, whose responses were particularly valuable for parameterizing the model.

Subsistence farming, in which most of the goods produced are consumed within the household, with minimal or no contribution to the market economy (Faurès and Santini, 2008; Waters, 2008), is practiced by approximately two billion people worldwide, in many rural regions and developing countries (Chakrabarti, 2016). In our model, the *subsistence* archetype prioritizes the preservation of traditional practices and cultural values, with little attention paid to improving animal breeding, feed quality, or herd management practices. This archetype emphasizes self-sufficiency and low costs, using natural resources to support livestock production without the use of external inputs. Commercial farming dominates in more developed, market-driven economies, driven by policy liberalization, infrastructure development, and rising population and income levels (Kuchimanchi et al., 2022; Reardon et al., 2019). In our model, the *commercial* archetype focuses on maximizing profits through efficient production methods, such as controlled breeding and selling of old livestock to improve the quality of the herd and the use of feed supplements to increase the number and weight of animals. The environmental archetype mimics an eco-friendly farming which is increasingly being adopted due to rising global awareness of sustainability and conservation issues (Willer et al., 2023). In our model, this archetype prioritizes the conservation of natural resources and the welfare of livestock over the maximization of profit.

The archetypes differ in their goals and decision-making criteria for when, how, and whether to implement management strategies related to grazing strategies, livestock sales, breeding and weaning strategies, and feed supplementation (Table 1). Although extensive livestock systems involve diverse and overlapping management practices, we classified them into distinct archetypes to facilitate analysis and comparison.

### *2.2. Model description*

A social-ecological approach was used to conceptualize the SOSLIVESTOCK model, which is structured in three interacting modules that simulate environmental, biophysical, and management aspects of extensive livestock systems (see Supplementary Material 1 for details).

**Table 1**
Management strategies related to grazing, livestock sales, breeding, weaning and feed supplementation strategies, used by the *subsistence*, *commercial* and *environmental* archetypes modeled, along with the effort required (in minutes or minutes per animal) to effectively implement these strategies. See Supplementary Material 1 for more details.

| Management strategy | | Definition | Effort | *Subsistence* | *Commercial* | *Environmental* |
|---|---|---|---|---|---|---|
| **Grazing** | Free grazing | Livestock graze freely throughout the entire pasture | – | Yes | Yes | Yes |
| | Rotational | The pasture is divided into four paddocks, and livestock move from one paddock to another | 30 min | Yes, at the end of the season | Yes, based on the average live weight of the herd | Yes, based on the carrying capacity of the paddock |
| **Livestock sales** | Ordinary sales | In the fall, male and surplus animals that exceed the desired herd size are sold | 5 min/ animal | Yes | Yes | Yes |
| | Sell non-replacement males | Sale of male animals that are not needed for breeding or herd maintenance | 5 min/ animal | Yes | Yes | Yes |
| | Sell old cows and non-replacement females | Sale of older cows and females that are not needed for breeding or herd maintenance. | 5 min/ animal | No | Yes | Yes |
| | Extraordinary sales | Animals sells at any time of the year | 5 min/ animal | No | Yes, when the body condition of livestock deteriorates | Yes, when the carrying capacity of the rangeland is compromised |
| **Breeding** | Uncontrolled | Breeding takes place at any time of the year | – | Yes | No | No |
| | Controlled | Breeding takes place in summer | 15 min | No | Yes | Yes |
| **Weaning** | Natural | At the age of 8 months | – | Yes | Yes | Yes |
| | Early | Between 1 and 7 months of age, depending on the mother's body condition | 5 min/ animal | Yes, if the mother dies prematurely | Yes, if the mother dies prematurely or her body condition falls below a threshold | Yes, if the mother dies prematurely |
| **Feed supplementation** | | Feed supplementation for animals below their minimum weight | 2 min/ animal | No | Yes | Yes |

The environmental and biophysical modules are based on the *Sequia-Basalto* model, originally developed in Cormas by Dieguez Cameroni et al. (2014), and later replicated in NetLogo by Soler-Navarro et al. (2023). It involves agents (cattle) moving through the space using grazing resources (pasture). The amount of pasture varies according to the amount of grass eaten by the cows, the season and a climate coefficient (Climacoef). Climacoef is a key parameter that modulates primary production. The social module includes the management decisions of each archetype, which depend on their goals and the prevailing environmental conditions. Each one of the strategies has a time-related cost (effort), which refers to the amount of time needed to successfully implement it (Table 1). Outcomes emerge from the social-ecological interactions and decisions, allowing us to evaluate how each archetype performs under climate-driven resource conditions in term of resilience and ecological, economic, and social sustainability (Table 2).

Each time step (one day) starts with grass growth, which is influenced by climate and season. Animal live weight is then updated based on grass consumption and can be supplemented if grass is insufficient. After consumption, cows grow and reproduce (when the required conditions exist), and a new grass height is calculated for the next day. Cows have a 50 % chance of moving to areas with the highest grass height, cattle prices are updated, and sales occur on the first day of the fall, with special sales during severe droughts. The time step ends with the calculation of the economic balance of the farm and the effort associated with the different management strategies implemented during this time step. Agents in our model are affected by stochasticity caused by animal movement, mortality, and pregnancy. The main procedures are shown in Fig. 1. We run 200 simulations over a forty-year period for each combination of archetype, Climacoef, and grazing management strategy, resulting in a total of 36,000 simulations.

**Table 2**
Indicators used to assess the performance of the three archetypal extensive livestock systems. For detailed equations, see Supplementary Material 1.

| Outcomes | Variable name | Definition | Units |
|---|---|---|---|
| **Resilience** | Probability of resistance | Inverse of the collapse probability (number of simulations in which a collapse occurs divided by the total number of simulations). | probability |
| | Time to collapse | Number of years the system resists before collapsing. | years |
| **Ecological sustainability** | Grass Height (GH) | Primary production (biomass). | cm |
| **Economic sustainability** | Animal Units (AU) | Number of animals in the system, considering the different grazing effects and feed requirements of different age groups in the herd. 1 AU = 380 kg. | AU |
| | Live Weight (LW) | State of the animals in terms of live weight. The grass height for live weight maintenance is defined as 5 cm. | kg |
| | Economic Balance (EB) | Difference between the income and expenses of the livestock system. Income is derived from the sale of livestock, while the only expense is the purchase of feed. | USD |
| **Social sustainability** | Effort (E) | Total time required by the farmer to implement different management strategies within the livestock system. | hours |
| | Wellbeing (W) | Ratio between economic balance and effort. | USD/ hours |

### 2.3. Sensitivity analysis

We conducted a local sensitivity analysis (one parameter at a time) to assess the robustness of the model by varying ±20 % of the values of 20

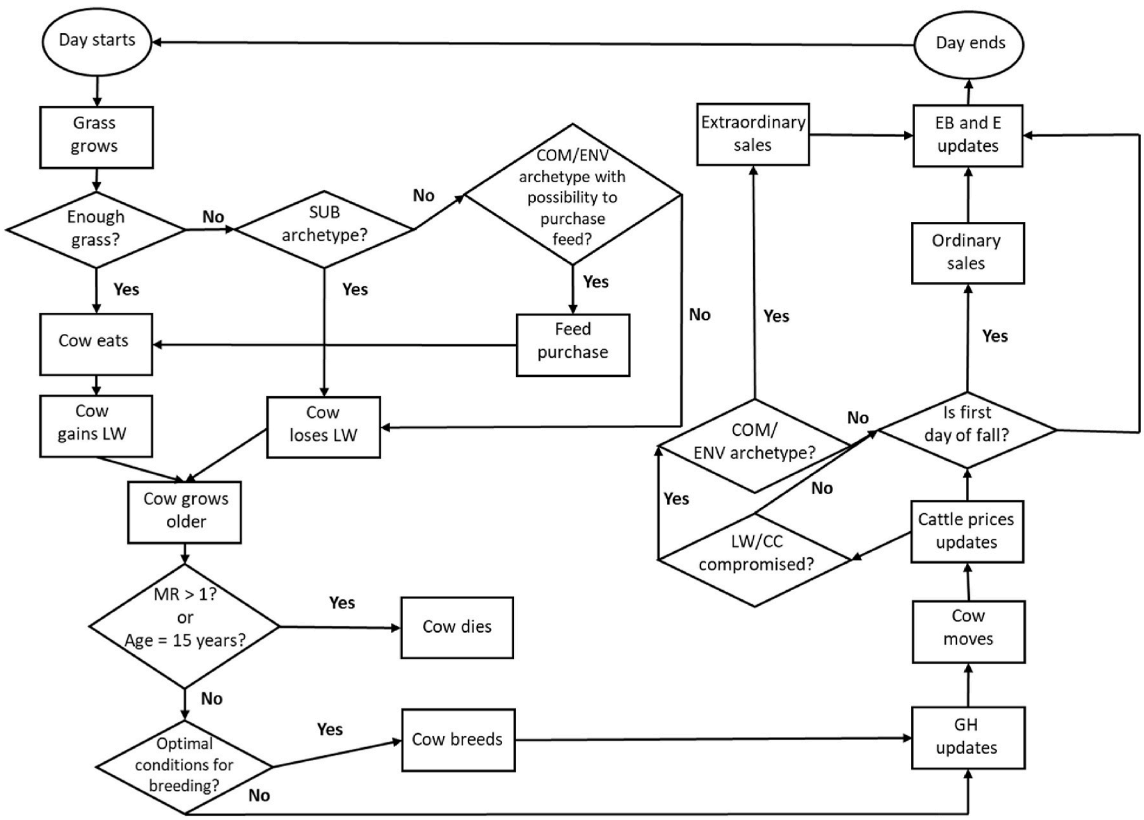


**Fig. 1.** Flow chart of the model during one timestep. CC, carrying capacity; COM, *commercial*; EB, economic balance; E, effort; ENV, *environmental*; GH, grass height; LW, live weight; MR, mortality rate; SUB, *subsistence*. See Supplementary Material 1 for more details.

management-related parameters from six categories: body weight, commercial-exclusive parameters, effort, feeding, perception, and stocking rate. The results indicate that the model is robust, as approximately 90 % of all parameter-variable combinations fall within the low-to-moderate sensitivity range (Supplementary Material 4).

### 2.4. Scenarios

To systematically explore the potential effects of climate change on primary productivity, scenarios were defined by combining variations in the Climacoef (ranging from 0.05 to 1.5 in increments of 0.05) with two grazing management strategies (free grazing and rotational grazing) across three archetypal livestock systems.

A Climacoef of one represents a year of "normal productivity", where primary production equals the historical average, referring to the business-as-usual climate conditions under which the livestock system has evolved and adapted. A value greater than one means “high productivity”. For example, a Climacoef of 1.5 represents a year with exceptionally favorable climate conditions, where primary production is 50 % above the historical average. Conversely, values below one represent “low productivity”, with extremely low coefficients (e.g., 0.3 or 0.2) reducing primary production by 70 % or 80 %, respectively. In our simulations, seasonal variation in primary productivity is maintained, but the effect of climate change on primary productivity, emulating its potential long-term and persistent impact, is assumed to be constant throughout the entire simulation period.

In a free grazing strategy, livestock have constant access to the entire pasture at all times, with no specific restrictions on their movement. This approach requires minimal infrastructure and labor because it relies on the natural grazing behavior of animals to find their own forage. In a rotational grazing scheme, the pasture is divided into four equal paddocks and livestock are moved from one paddock to another on a scheduled basis. The duration of grazing in each paddock and the intervals between grazing events are determined by management goals (Table 1).

### 2.5. Outcomes

To assess resilience, this study defines it as the capacity of the system to persist under the conditions established in each scenario, determined by Climacoef and the grazing management strategy. Two proxy indicators are used to assess resilience: i) the inverse probability of system collapse under the given conditions, and, for cases where systems do collapse, ii) the time elapsed until collapse occurs. In the current version of our model, system collapse only occurs when the ecological sustainability threshold is exceeded, meaning that grazing resources are insufficient to sustain the livestock, causing the number of animals to drop to zero.

To assess sustainability, we used six key indicators representing the ecological, economic, and social dimensions of system performance. For ecological sustainability we used grass height (*GH*) as an indicator of the state of grazing resources within the system, analogous to the use of biomass in similar studies (Jakoby et al., 2015; Martin et al., 2014, 2016). Economic sustainability was measured by calculating the economic balance (*EB*) as the net income of each archetype. The economic balance accounts for income from livestock sales (determined by the number of animals sold and their weight at the time of sale) and expenses of feed purchases (Walters et al., 2016). For social sustainability, we developed a wellbeing indicator (W), which represents the ratio between the economic balance (EB) and the effort (E) required to implement the different management strategies. Workload has been used in other studies as a proxy for social sustainability (Walters et al., 2016), and has been identified as a factor closely linked to farmers’ wellbeing and their perception of their quality of life, which influences the maintenance of the livestock farming activity and generational renewal (Bertolozzi-Caredio, 2024). Here, effort is measured in time or time per animal, with the duration for each management strategy based on farmer interviews and expert knowledge. Definitions for each variable are summarized in Table 2, while the corresponding equations can be found in the Supplementary Material 1.

The simulation results for each archetype are compared based on the average of the 200 runs at the simulation end time and 95 % confidence intervals. We use the non-overlapping confidence intervals between archetypes to indicate potential significant differences. To enhance clarity, we present the resilience and sustainability outcomes of the free-grazing strategy, while the tradeoffs analysis provides a comparison between free grazing and rotational grazing.

## 3. Results

### 3.1. Resilience under climate-driven changes in grazing resources

System resilience is higher for the *environmental*, *commercial*, and *subsistence* archetypes at scenarios where the primary productivity has been reduced by 70 %, 55 %, and 50 %, respectively (Fig. 2a). None of the archetypes collapse when primary productivity declines by up to 50 %. However, below this threshold, the probability of collapse increases sharply, with the *environmental* archetype remaining the most resilient, followed by the *commercial* and *subsistence* archetypes.

Regarding the time to collapse (Fig. 2b), the *environmental* archetype withstands the most extreme conditions, persisting for up to 7 years even when primary productivity has been reduced by 80 %. Under slightly less severe conditions, the *commercial* archetype outlasts the *environmental* one, but beyond this threshold, the *environmental* archetype no longer collapses, whereas the *commercial* archetype continues to fail until Climacoef exceeds 0.4. The *subsistence* archetype, which collapses almost immediately under extreme conditions, shows a marked increase in survival time when Climacoef is above 0.4, reaching up to 12 years. This archetype no longer collapses when Climacoef exceeds 0.45.

### 3.2. Sustainability under climate-driven changes in grazing resources

Above the threshold where no archetype collapses, the *environmental* archetype consistently maintains the highest grass height (Fig. 3). Below this threshold, there are no significant differences between the *environmental* and *commercial* archetypes (Fig. 3). Notably, at Climacoef of 0.45, the *commercial* archetype experiences a sharp increase in livestock numbers (Fig. 4a), which subsequently leads to a decline in grass height due to higher grazing pressure (Fig. 3).

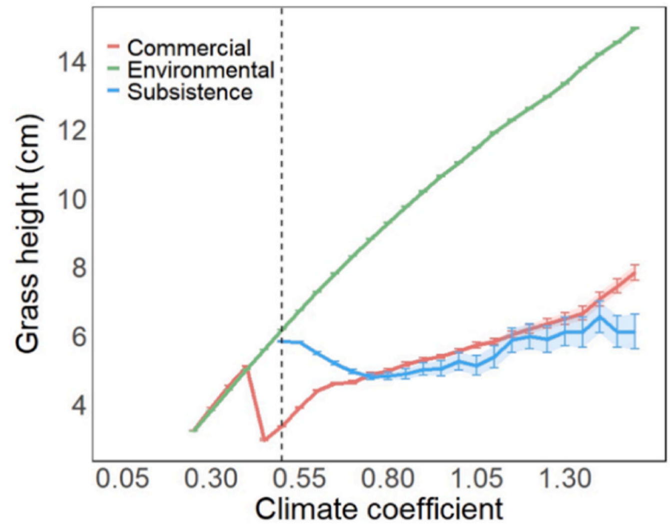


**Fig. 3.** Grass height under different climate conditions for each archetype in free grazing conditions. Dashed vertical line: threshold beyond which none of the three archetypes collapse. Shading: 95 % confidence intervals.

In the scenarios where the primary productivity has been strongly reduced, the *environmental* archetype maintains the highest economic balance (Fig. 4b). However, beyond this threshold, the *commercial* archetype consistently outperforms the others. Economic balance is closely related to the livestock numbers and their body weight at sale: while the *environmental* archetype compensates for fewer animals with better weight across all conditions, the *commercial* and *subsistence* archetypes rely on higher livestock numbers despite poorer body condition (Fig. 4a and c).

Under the most extreme reductions in primary productivity, wellbeing is similar for the *environmental* and *commercial* archetypes (Fig. 5). At a Climacoef of 0.45, wellbeing in the *commercial* archetype drops abruptly due to a sudden increase in livestock numbers (Fig. 4a), increasing the effort required for farm management. This trend reverses at Climacoef 0.5–0.6, after which the *commercial* archetype shows the highest wellbeing. The *environmental* archetype shows steady improvement as Climacoef increases, reaching similar wellbeing levels to the *commercial* archetype at Climacoef 1.5. The *subsistence* archetype exhibits intermediate wellbeing between Climacoef 0.75 and 1, but remains the lowest outside this range.

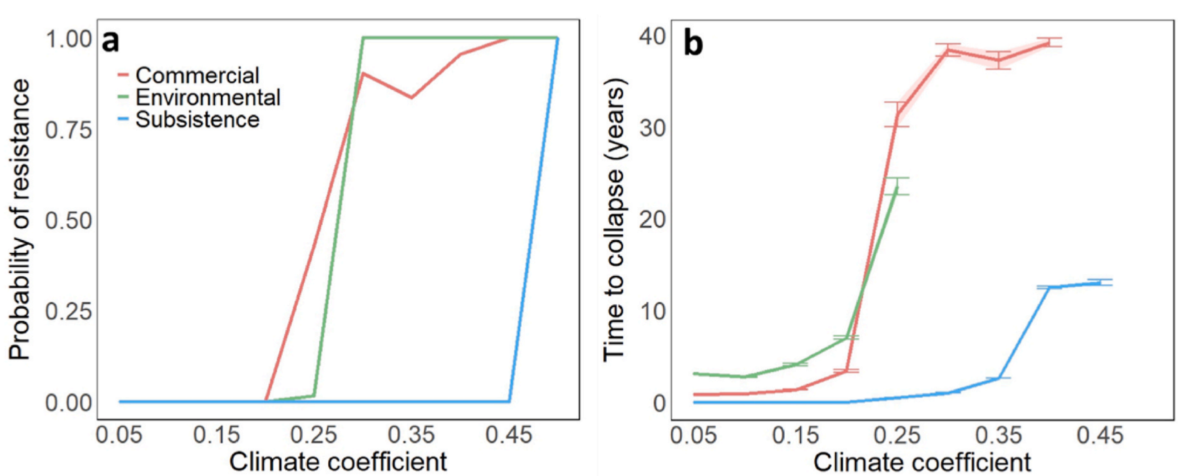


**Fig. 2.** Probability of resistance (a) and time to collapse (b) under different climate conditions for each archetype in free grazing conditions. Climate coefficient values represent ecosystem primary production (e.g., 0.25 corresponds to a 75 % reduction in primary production). Shading: 95 % confidence intervals.

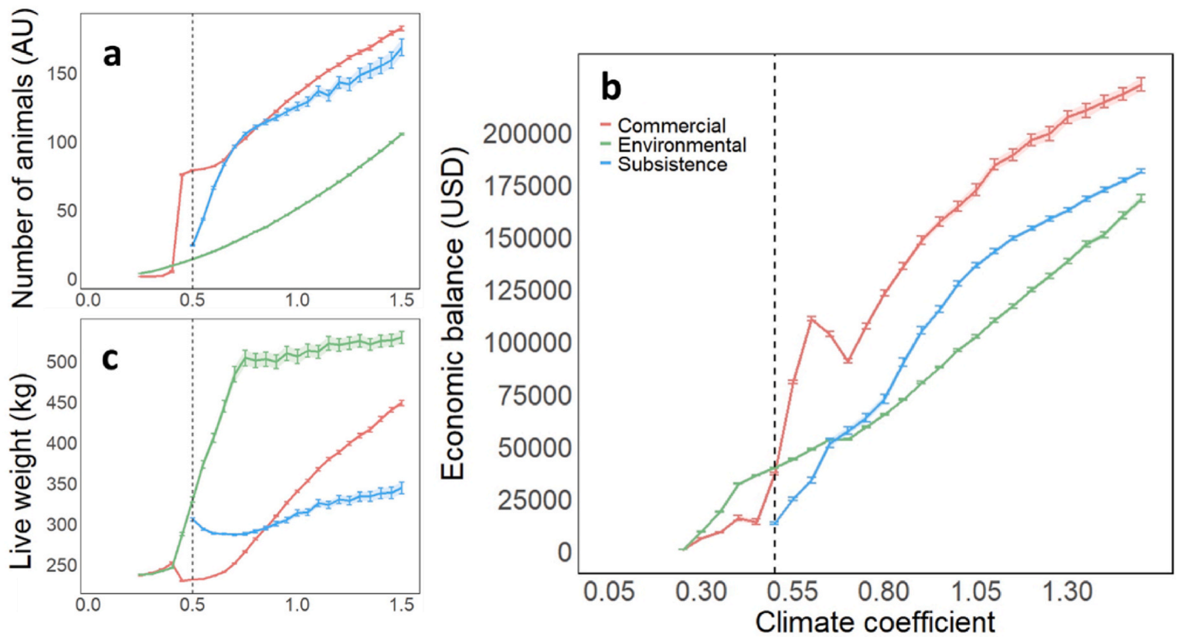


**Fig. 4.** Number of animals expressed in animal units (a), economic balance (b) and live weight of breeding females (c), under different climate conditions for each archetype in free grazing conditions. Dashed vertical line: threshold beyond which none of the three archetypes collapse. Shading: 95 % confidence intervals.

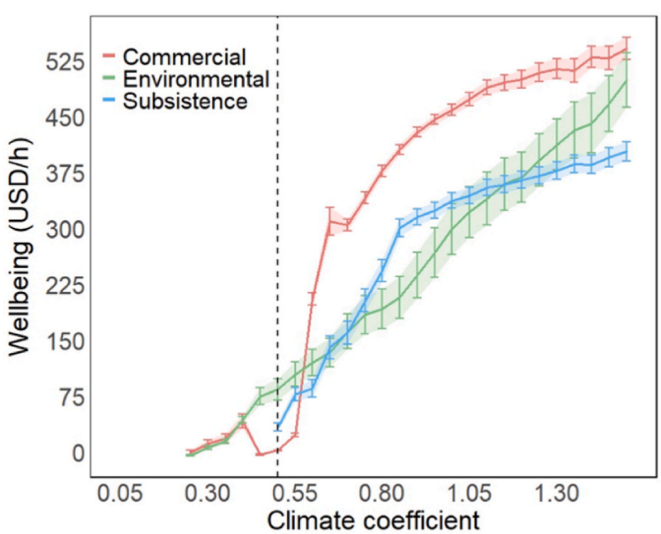


**Fig. 5.** Wellbeing under different climate conditions for each archetype in free grazing conditions. Dashed vertical line: threshold beyond which none of the three archetypes collapse (climate coefficient of 0.5). Shading: 95 % confidence intervals.

### 3.3. Emerging tradeoffs

Across all scenarios, rotational grazing yields lower social and economic sustainability outcomes for all archetypes but improves ecological outcomes compared to free grazing (Fig. 6a, b, 6c). The *commercial* archetype experiences the sharpest decline in wellbeing, especially under normal and high productivity scenarios (Fig. 6b and c). In contrast, the *subsistence* archetype achieves the most balanced performance across sustainability dimensions, even outperforming the *commercial* archetype under these conditions, opposite to the trend observed under free grazing (Fig. 6b and c). Under the free grazing strategy, sustainability outcomes vary with primary productivity. At low productivity, the *environmental* archetype balances the three dimensions best. At normal productivity, the *commercial* archetype excels in social and economic sustainability but at an ecological cost, while the *subsistence* archetype follows a similar but weaker pattern. This trend remains under the high productivity scenario, though the *environmental* archetype significantly improves across all dimensions, nearly matching the *commercial* archetype in social and economic aspects.

## 4. Discussion

In this study we explore the potential long-term and persistent impacts of climate change on primary productivity and their effects on the resilience and sustainability of three archetypes of extensive livestock systems (*subsistence*, *commercial*, *environmental*) representing the diverse spectrum of livestock farming practices worldwide. Our analysis identifies key resilience thresholds and tradeoffs among social, economic, and ecological dimensions of sustainability. While this study does not aim to identify a universal set of management strategies suitable for all extensive livestock systems, our findings shed light on the implications for the archetypes compared, and offer potential pathways to enhance both their resilience and sustainability under the uncertainty of climate change.

### 4.1. Tipping point thresholds in climate change resilience

Our simulations reveal the existence of a threshold beyond which systems collapse, with different management practices influencing this threshold, either raising or lowering it, but never eliminating it. Our results indicate that all three archetypes can resist a 50 % reduction in primary productivity but more severe declines push the systems to their limits. While the *environmental* and *commercial* archetypes exhibit greater resilience, even they cannot withstand such extreme conditions indefinitely. Under these scenarios, management practices, while beneficial, are ultimately insufficient, leading to the inevitable collapse of the systems.

The *environmental* archetype is the most resilient, capable of persisting even under extreme conditions where primary productivity has declined by 70 %. The *commercial* archetype follows in resilience, able to persist under reductions of up to 55 % in primary productivity. In contrast, the *subsistence* archetype is the most vulnerable, collapsing

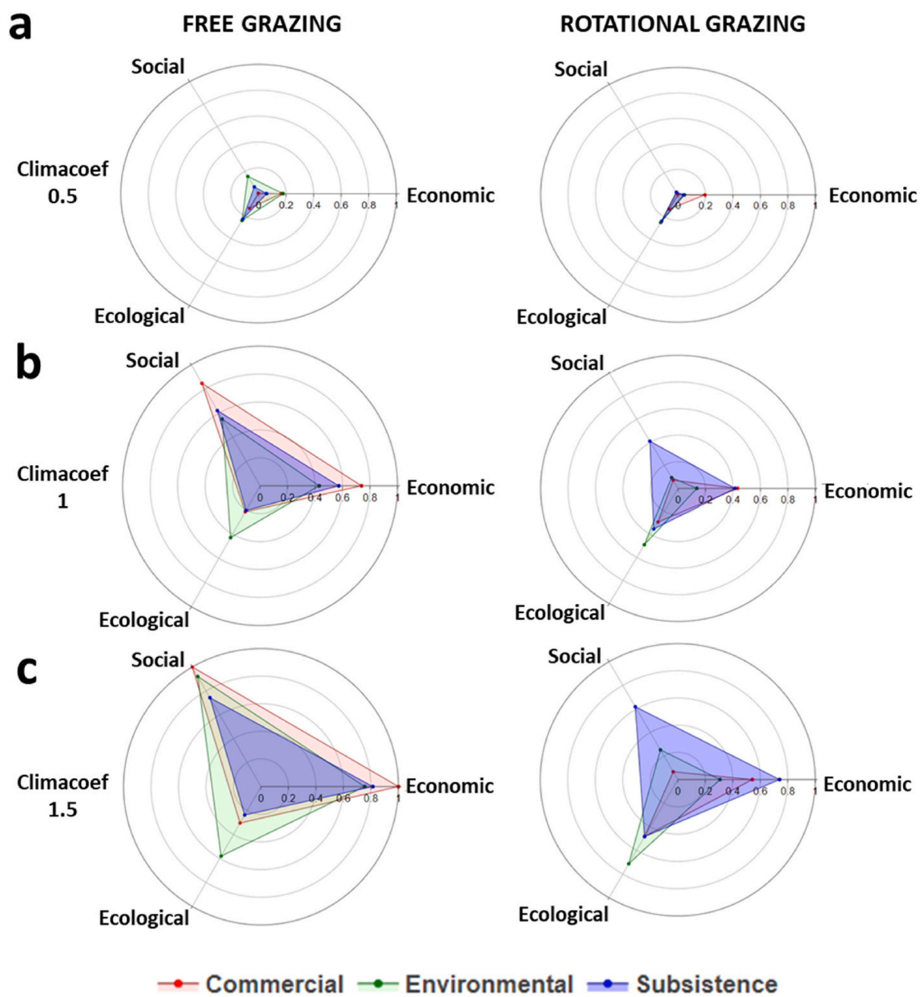


**Fig. 6.** Amoeba plots illustrating the ecological, economic, and social sustainability across the three archetypes under free grazing and rotational grazing strategies and three climate conditions (0.5, 1.0, and 1.5 climate coefficients).

under less severe reductions in primary productivity. This difference in resilience is largely due to the management practices adopted by the *environmental* and *commercial* archetypes, particularly the use of supplementary feed, which allows them to maintain livestock productivity even when local natural resources are scarce. Previous studies have shown that subsistence societies are particularly susceptible to collapse under adverse climate conditions (Ember et al., 2020; Lima et al., 2023) as they often lack the economic resources needed to purchase forage (Eeswaran et al., 2022; Thornton et al., 2014). Solutions to enable sustainable resource management are subsidizing forage acquisition during drought periods to enhance the adaptive capacity of subsistence systems (Lipper et al., 2014), and innovating and combining their traditional practices with modern production techniques (Singh and Singh, 2017; Zheng et al., 2024). For example, Megersa et al. (2014) observed that forage collection and storage practices reduced livestock mortality by 20 %.

### 4.2. Ecological, economic and social sustainability

The *environmental* archetype shows the best ecological outcomes across all scenarios of primary productivity change due to its focus on animal welfare and ecosystem preservation, but this comes at the cost of lower economic performance resulting from reduced livestock numbers. In contrast, the *commercial* archetype excels economically due to its production and market-driven approach, which also translates into the highest social sustainability, as wellbeing is determined by both economic balance and the effort required to sustain the activity. Despite its economic tradeoff, the *environmental* archetype achieves wellbeing levels similar to those of the *commercial* archetype under extreme scenarios because maintaining fewer animals in better body condition reduces both the effort per animal and the need to purchase additional forage, lowering the overall workload. The economic cost of the *environmental* archetype could be offset through mechanisms such as payments for ecosystem services (Pérez-Rubio et al., 2021; Song et al., 2023), or quality certification labels (Blackman and Rivera, 2011). If such incentives were incorporated into the model, the *environmental* archetype would likely emerge as the most sustainable and resilient extensive livestock system under all potential primary productivity change scenarios. However, without such compensation, the *commercial* archetype management strategy would perform better in systems that may benefit from climate change in terms of primary productivity or be minimally affected by it. In these cases, such systems should implement measures to reduce the negative impact of their management on the ecosystem.

Despite the recognition of rotational grazing as a strategy to improve ecological sustainability and pasture management (Teague et al., 2013; Teague and Barnes, 2017), empirical results have shown that the differences in its benefits compared to free grazing are not as significant as expected (Augustine et al., 2020; Porensky et al., 2021; Venter et al., 2019). Our findings align with this, as we found that under normal and high primary productivity scenarios, free grazing results in higher economic and social sustainability across all archetypes, while rotational grazing yields better ecological outcomes.

### 4.3. Limitations and future applications

To maintain simplicity, our model relies on several assumptions. Effort was assumed to be the same across archetypes, though in practice, commercial systems often require less manual labor than subsistence systems due to mechanization (FAO, 2022; Romano et al., 2023). Livestock numbers were limited to what one person can manage, overlooking the role of hired labor, which increases costs but reduces workload. Additionally, effort was constrained to five management practices, underestimating the labor intensity of extensive livestock farming, which often involves longer working hours than other occupations (Hostiou et al., 2020; Duval et al., 2021).

Collapse in our model is simplified as exceeding ecological thresholds without considering other biophysical or socioeconomic constraints. Economic factors (e.g., market fluctuations, policy changes) can also lead to collapse by making livestock farming economically unviable (Dos Reis et al., 2020; Lapola et al., 2014). In reality, many farms may abandon the activity before losing all livestock, especially when the number of animals falls below the economically viable thresholds (Næss and Bårdsen, 2010; Martin et al., 2014, 2016). Social factors can also drive collapse; for example, high workloads can reduce wellbeing and discourage continuation or generational renewal (Coopmans et al., 2021; Bertolozzi-Caredio, 2024). Consequently, our model may overestimate resilience by not incorporating these economic and social viability constraints. Integrating these factors would significantly improve future model iterations.

Climacoef is a dimensionless index that represents how primary productivity is affected by climate, relative to historical average values. For the purposes of this study, this coefficient was held constant in each simulation, but it can be varied annually or seasonally to explore inter- and intra-annual climate variability (Dieguez Cameroni et al., 2014). Moreover, if historical variation is known for a specific case study, empirical data can be incorporated to simulate the dynamics of that particular system (Dieguez Cameroni et al., 2014). Future applications could also incorporate seasonal grass growth patterns or diverse landscape configurations to better reflect local conditions.

## 5. Conclusions

SOSLIVESTOCK is a simplified yet flexible model that simulates the dynamics of three extensive livestock system archetypes: *subsistence*, *commercial*, and *environmental*, under climate-driven changes in primary productivity and two grazing strategies. Using this model, we explore the long-term and persistent impacts of climate change on primary productivity, and their implications for the resilience and sustainability of these archetypes.

Our results show that all archetypes face collapse threshold, with the *environmental* and *commercial* archetypes showing greater resilience than the *subsistence* archetype. The *environmental* archetype is the most resilient and sustainable under moderately adverse conditions. However, no single strategy performs best across all situations. The *environmental* archetype offers strong ecological outcomes with lower economic returns, while the *commercial* archetype achieves economic gains at the cost of greater ecological tradeoffs. The *subsistence* archetype is the most vulnerable due to limited economic resources and market access.

Our findings highlight the need for targeted adaptation strategies, especially for subsistence farmers, such as subsidizing fodder supplies during pasture scarcity. Promoting environmental focused management increases system resilience under adverse conditions, while economic archetypes require efforts to reduce ecological impacts. Enhancing the economic viability of the *environmental* archetypes, through payments for ecosystem services, can help balance tradeoffs and support more sustainable and resilient livestock systems under climate change. Overall, our study highlights the importance of context-specific policies and adaptive strategies to help balance tradeoffs and build long-term resilience across diverse livestock systems in a changing climate.

## CRediT authorship contribution statement

**Diego J. Soler-Navarro:** Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Alicia Tenza-Peral:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **Marco A. Janssen:** Writing – review & editing, Supervision, Conceptualization. **Andrés Giménez:** Writing – review & editing, Conceptualization. **Irene Pérez-Ibarra:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126004.

## Data availability

Link to the ABM: https://www.comses.net/codebases/2f4f121c-10c6-45e9-9742-f5d8d7fbf9b5/releases/1.1.0/

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