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Ecological–Economic Feedback Modeling for Regional Intelligence: A Systems Analysis of Xilingol's Pastoral Economy

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Abstract

The research will attempt to formulate an integrated ecological economic feedback model that will describe the dynamics of the pastoral economy in Xilingol long-term. It researches on the interaction of grassland biomass, livestock population behavior, household economic choices, and policy interventions via strengthening and balancing feedbacks. The aim is to find leverage points to ecological sustainability and produce the regional system of intelligence that can predict the risk of degradation and lead to adaptive governance.The study uses a system dynamics modeling technique whereby ecological, economical; climatic and policy subsystems are integrated into a cohesive feedback mechanism. The calibration is done with the help of empirical data in the form of NDVI records, livestock census, climatic records, and government policy archives. Stock-flow frameworks, nonlinear models, degradation limits are developed to determine the four scenarios in 30 years of continuation and intensification of grazing: continuity with baseline, increased grazing, and rotated grazing; continuity with intensity increase of subsidies. Validation involves historical fit test, sensitivity test, structural test, and extreme condition test.Even though many studies are currently carried out on grassland degradation or pastoral household behaviour, few of them combine ecological, economic, and institutional processes in the same dynamic framework. The article provides a new ecological-economic feedback reproduction that is specific to Xilingol and locates it in a regional intelligence paradigm. It is a predictive, feedback-sensitive instrument, which gives the policy makers an opportunity to anticipate the potential ecological dangers in the long term and assess the unintended impacts of interventions like subsidies or stocking limits.Findings have shown that the pastoral economy is controlled by connected reinforcing and balancing loops, which generate overshoot-and-collapse dynamics. Ecological thresholds are traversed gradually yet permanently under both baseline and intensified grazing conditions and cause decreased biomass, low livestock productivity, unpredictable income and eventual system instability. Rotational grazing retains biomass at 92-97% original values and stabilizes the size of the herd. The intensification of subsidies increases the short-term income and enhances the incentives of herd expansion at the expense of degradation acceleration in case ecological constraints are not considered.The article contributes to the ecological-economic systems theory by showing the combination of delayed feedbacks, nonlinear ecological reactions and economic incentives in the formation of pastoral trajectories. It is methodologically adaptable in bringing ecological processes, household decision behavior and policy instruments together in one structure of system dynamics, which provide a base to the intelligence of the environment in regions. The model is useful in that it can identify the mechanisms of policy resistance early, detecting them beforehand, and the framework is replicable across the analysis of pastoral SES in other areas.

Keywords: *Pastoral Economy; Ecological–Economic Feedback; System Dynamics; Xilingol; Regional Intelligence; Grassland Resilience.*

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Introduction

Pastoral areas in the world are facing growing strains that are caused by ecological degradation, climate change, and deep-seated changes in land-use activities. Among these areas, one of the most significant pastoral social-ecological systems in the East Asia is Xilingol that is located in the Inner Mongolia Autonomous Region in northern China. The topography is comprised of mainly of temperate steppe grasslands that have traditionally sustained nomadic and semi-nomadic herding communities of livestock. These grasslands have over the centuries developed in a careful balance between the processes involved in the natural regeneration and the grazing of livestock. However, in recent decades this balance has been disrupted more often due to altered climatic patterns, population growth, the intensification of herds through the market and policy changes transforming the incentives of pastoralists to live (Mei et al., 2025).

The environmental base of Xilingol has been weakened particularly. The empirical evaluations indicate an increasing degradation of grasslands, decreased productivity of vegetation, diminished soil fertility with an increased exposure to drought cycles. These changes pose a threat not only to the ecological stability, but also to the socio-economic welfare of pastoral households whose means of livelihood largely relies on availability of the sustainable biomass(Zhang et al., 2025). The fact of interdependence of these environmental and economic issues underlines the idea that Xilingol is not one particular environmental issue but rather a set of interactions of the human actions, ecological processes, and institutional structures in various ways.

Conventional policy measures have been made to reduce degradation and enhance environmental performance by banning grazing, ecological compensation plans, fencing initiatives, stocking quotas, and rotating grazing plans. Nonetheless, such interventions tend to have inconclusive or non-target outcomes due to the lack of consideration of underlying systemic feedback processes. Policies which seem to be useful in the short run can initiate reinforcing loop mechanisms which lead to long-term unsustainability, particularly when ecological processes have time delays or threshold effects. In the case of subsidies that raise household income, subsidies can lead to an increase in the size of the herd unwanted, leading to more grazing and faster degradation unless coupled with ecological restrictions. Similarly, sudden restrictions on grazing can cause a reduction in pressure, but can undermine local incentive systems, decrease livestock productivity or change the pressure of grazing to uncontrolled lands(Liang et al., 2025).

The following situation creates a critical research gap: although the ecological and socio-economic literature is rich, no unified models can capture a feedback loop, nonlinear interactions and adjustments to dynamics that would have played a combined role in determining the pastoral nature of the history in Xilingol. The current studies are more inclined to examine the ecological degradation, household economic behavior, or policy effects separately. The number of studies that use such a rigorous systems-based approach that integrates ecological processes (e.g., biomass regeneration, rate of degradation), economic choices (e.g., herd management, income strategies) and policy tools into a consistent analytical framework are few (W. H. Zhang et al., 2023).

The study fills this gap by formulating an ecological-economic feedback model through the system dynamics methodology. The aim is to find out how the ecology of grassland, pastoral household choices, and institutional intervention interact and how they co-evolve through time and to assess how various policy options can determine future ecological and economic results. System dynamics is especially well adapted to pastoral settings since it explicitly displays accumulations (as biomass and size of herd), feedback mechanisms, time delays, which are characteristics of socio-ecological systems (Miao et al., 2021). Using this method in Xilingol, the research aims at uncovering concealed systems of policy resistance, pinpointing hot-spots of intervention, and setting a basis of predictive regional intelligence.

The idea of regional intelligence is defined as the fusion of ecological surveillance, socialeconomic variables and forecasting modeling to aid in proactive and reactive choice. Regional intelligence can be used in the pastoral setting by policymakers to predict levels of degradation, measure long-term trade-offs, and coordinate interventions with ecological regeneration dynamics. Such an intelligence structure could only be established by a sound concept of the temporal interaction between ecological constraints and economic incentives, which system dynamics modeling is the only means to acquire such knowledge.

Thus, the goals of this research are four:

(1) to develop an integrated ecological-economic feedback model that serves as the reflection of the pastoral system of Xilingol;

(2) to determine the important reinforcing and balancing loops that drive the behavior of a system;

(3) to model other policy options and compare their ecological and economical implications;

(4) to transform these insights into a functioning regional intelligence system that can be used to inform adaptive strategies of governance.

The scholarly value of this article can be associated with the development of the ecological-economic systems theory in terms of the feedback-based interpretation of pastoral dynamics, the usefulness of the system dynamics in pastoral policy research, and the empirical evidence on the long-term sustainability challenges of Xilingol. In practice, the model provides a policy support program to policymakers who need to consider a balance between ecological rehabilitation and livelihood security and emphasizes the necessity of time-sensitive, agent-based, and context-sensitive intervening strategies.

Theoretical Framework

Pastoral economies, like Xilingol are based on a highly-integrated socio-ecological system where ecological, economic as well as institutional sub-systems co-evolve. A solid theoretical background is needed in this research so that it is possible to explain the application of system dynamics and feedback modelling and to place the pastoral problems facing Xilingol in the wider context of the socio-ecological resilience, ecological economics and regional intelligence literature. Each of the subsections below has a preceding contextual paragraph in order to meet the journal format.

The theoretical framework is formed on the basis of five pillars:

(1) ecological-economic systems theory;

(2) pastoral socio-ecological structures and their behavioral patterns;

(3) regional intelligence as a paradigm of governance;

(4) system dynamics theory and its applicability in feedback modeling; and

(5) the increasing amount of literature that implements such models on grassland and pastoral management.

Ecological-Economic System Theory.

The conceptualization of ecological-economic system views the ecosystems and human economic activity as a set of interdependent units in a larger system that is regulated by energy, material, and information flows. In pastoral lands, this interdependence is made more concrete: the production of livestock is based on the ecological carrying capacity, and the regeneration of ecology is subject to the intensity and the manner of the pressure of grazing. Classical ecological economic models lead to emphasis on non-linearities, thresholds, resource scarcity restrictions, and the concept that economic processes have to eventually act within biophysical bounds.(Xu and Wu, 2016)

Grassland biomass is a supply of ecological stock and economic input in the steppe of Xilingol. Constructive degeneration of biomass directly causes a decrease in productivity of livestock, which results in an unstable production of income, which promotes compensatory measures such as the expansion of herd, which in turn can have an additional effect on the ecosystem. This is a reinforcing loop that has the potential of leading to long-term degradation when neglected. On the other hand, degradation-based downfalls in biomass trigger balancing cycles that limit livestock population by decreasing the availability of forage. The combination of the reinforcing and balancing loops is the essence of the ecological-economic system theory and has a severe impact on the pastoral dynamics.(Kolås, 2014)

This theory also emphasizes the relevance of time lags, e.g. slow biomass recovery, lagged economic reactions, can generate oscillatory, unsteady or counterintuitive system behaviour. It is important to note that such characteristics are the reasons why traditional methods of policy, which are based on the assumption of linear cause-effect relationships, are frequently not effective.

Pastoral Socio-Ecological Systems

Socio-ecological systems (SES) are pastoral regions with a high level of interaction between the variability of the environment, livestock numbers, domestic policies, and governments. The literature on pastoral SES has singled out four attributes that are applicable at Xilingol:

Climate dependence: There is a disproportionate impact of precipitation variability and droughts on the growth of grassland.

Behavioral adaptiveness: Herders change the approach with the help of herd composition, mobility, feed supplementation, or market involvement.

Cultural norms and traditions: The pastoral identity affects the grazing patterns, herd preferences and the ecological risk perception.(Zhang, 2023)

Institutional background: The policy by the state on the use of the grasslands brings external incentives that change the behavior of households.

Empirical evidence in Asia and Africa shows that in the past, pastoral SES are sometimes found to be at the border of ecological boundaries. When these cross, there is loss of vegetation cover, decrease in resilience and sluggish or unpredictable recovery. It is also a feature of research that path dependency: the choices made in the past influence the present state of the ecological system, which consequently affects the choice that will be made in the future, creating cumulative and irreversible curves. These attributes are another reason to believe in a feedback modeling approach.

Regional Environmental Governance Intelligence

There is a need to contextualize this study to the context of governance before discussing certain techniques of modeling. The term regional intelligence has become a strategic paradigm of environmental and resource management. It is the methodical combination of data, predictive modeling, ecological signs, socio-economic analysis and policy assessment instruments to enhance anticipatory and adaptive decision-making.

The regional intelligence systems especially apply well to Xilingol since the conventional command and control intervention practices have failed to turn around the degeneration patterns. The policies should rather consider:(Kaushal et al., 2021)

- premature indicators of ecological distress;
- overall effects of herd management decisions;
- interrelations, between subsidies, domestic incentives and ecological states;
- resource fluctuations due to climate changes;

when and how sensitive interventions are.

The integration of ecological-economic feedback modeling with a regional intelligence system makes the policy more sensitive to system dynamics and also enables the policy makers to be able to experiment with alternative strategies before practising them.

System Dynamics Theory

The methodology of system dynamics (SD) was created by Forrester to analyze systems which can be described as systems with feedback loops, accumulations (stocks), flows, and delays. SD is also very applicable in the representation of pastoral systems due to a number of reasons.

To begin with, pastoral economies hold obvious stocks: biomass of grassland, the number of herds, income, and soils organic matter. These stocks increase or decrease with time depending on the flows like regeneration of biomass, consumption by grazing, birth of livestock and sales.(The World Bank, 2019)

Second, the behavior of a system is controlled by feedback loops, which are reinforcing and balancing in nature. Change is reinforced (e.g., larger herds lead to greater income, and larger incomes lead to larger herds). Balancing loops work against change (e.g., degradation decreases the amount of forage, which curtails herd growth).

Third, SD is a model that explicitly represents delays, e.g. the time lag between implementing a policy and ecological response, or pasture degradation and subsequent loss of income. These delays also tend to generate wavy patterns, rampage and degeneration or resistance to policy.

Fourth, SD facilitates the testing of the implications of various grazing rules, subsidy schemes and climate futures through the use of scenario simulation. This ability is a key to policy-making and is a foundation of the regional intelligence strategy.

Feedback Models of Grassland and Pastoral Management

There is an increasing literature in the application of systems modeling to grassland, rangeland and pastoral management. Mongolian, Kazakh and Australian and East Africa studies have demonstrated that degradation usually arises as a result of interacting feedbacks with stocking rates, precipitation cycles, market incentives, and state interventions. The models show that a minor perturbation can cause major shifts in the system provided the feedback structures drive the system out of ecological limits.(N. Zhang et al., 2023)

Although there has been this development, there are still some gaps. Most of the studies are concentrated on environmental processes and few are integrated with the household economic strategies or policy instruments. Some of them rely on econometric models that only rely on correlations but not processes. Only a very small number of them integrate ecological, economic, and policy dynamics into one temporally explicit feedback model. This study helps fill this gap by developing a composite model tailored in particular to the socio-ecological situation at Xilingol.

Methodology

The methodological approach that is adopted in the current research is rooted in system dynamics which is a field aimed idly at researching the temporal behavior of complex systems that operate under the influence of feedback loops, a non-linear behavior, accumulations and delayed responses. Pastoral economy of Xilingol has all these features and system dynamics is not only suitable but also necessary to know about the development of its ecological-economic processes(Peter et al., 2024). Each of the subsequent subsections describes, in more detail, the area of the study, data sources, conceptual modeling steps, the construction of stock-flows, mathematical formulation, the development of scenarios and the validation procedures. All the components are presented in a paragraph to make them clear, coherent, and in accordance with the guidelines of the journal.

Study Area Description

Xilingol League, an area within eastern Inner Mongolia Autonomous Region of China, has been used as the ecological site in this study because it is sensitive ecologically and relies on livestock grazing as a source of their economic benefit. The area itself is approximately 200,000 km 2 of temperate grass, with Stipa grandis, Leymus chinensis and Artemisia frigida as its primary species. It has semi-arid continental climate with precipitation of about 250 to 400mm in annual round figures, but with a great deal of uneven space and time distribution. Summers are very brief and rainy period, whereas winters are very long and snowy, usually until -30degC. Such climatic characteristics mean that the vegetation growth is highly changeable and forms a system prone both to stochastic shocks and chronic degradation stresses.(Xing et al., 2025)

Traditionally, pastoral economy of Xilingol is defined by mobile herding but with administrative reforms and sedentarization, mobility has been brought down slowly. Liberalization of markets since the late 1990s encouraged the growth of the herd, especially in sheep and cattle. At the same time, policy interventions to reduce degradation; including grazing prohibitions, rotating grazing implementation, stocking caps, and ecological compensation schemes, have tried to trade off ecological integrity and livelihood requirements. The area is therefore a dynamic example of interwoven ecological processes, economic behaviours and forms of governance and hence the existence of a strong system dynamics approach to take these interdependencies into account.

Data Sources

Robust system dynamics modeling is based on data integration. In this study, ecological, economic, climatic, and policy data were obtained using a variety of sources, which were reputable to guarantee that the marginal data are triangulated and accurate in calibration.

Satellite-based observations of Normalized Difference Vegetation Index (NDVI) provided the ecological data, as the satellite data provide comprehensive estimates of vegetation cover over prolonged durations. These data are extracted in the MODIS/Terra archives and they can be considered to give fine-grained temporal variation in biomass productivity. Additional ecological data were gained through grassland degradation appraisal released by local environmental agencies and field-based vegetation survey to gauge species composition, percent cover, and soil properties. Additional evidence in the calibration of biomass regeneration functions was gathered through ecological carrying capacity reports issued by the Ministry of Agriculture in China.(Gabriele et al., 2022)

The data on the economy and livestock were obtained through annual livestock censuses and statistical yearbooks available from the government of Xilingol. These sources record the size of the herd, herd composition (sheep, goats, cattle), the outputs of production, prices, and household income structures. Such information was necessary in building income equations, herd dynamics, and economic decision-making elements in the model.

Climatic inputs such as monthly precipitation, temperature data, and drought indices (Standardized Precipitation Index) were sourced from the China Meteorological Administration. Climate variables play a major role in the rate of vegetation growth, and they were factored into the biomass regeneration formulation.

Government policy archives were searched to find the policy information, such as the documentation of grazing bans, subsidy disbursement initiatives, stocking quotas, and fencing restrictions. These documents offered parameters to model the institutional interventions and know when, how big, and the intended results of such interventions.

Table 1 shows a summary of the key datasets that are employed and on which the models are constructed.

Table 1. Summary of Data Sources and Their Model Functions

Data Type	Source	Model Function
NDVI Vegetation Index	MODIS/Terra Satellite	Calibration of biomass regeneration dynamics
Grassland Degradation Records	Regional Environmental Bureaus	Parameterization of degradation thresholds
Livestock Census	Xilingol Statistical Yearbooks	Construction of herd population and income equations
Climatic Records	China Meteorological Administration	Integration of precipitation and drought impacts
Policy Documents	Local Government Archives	Modeling subsidies, grazing limits, and enforcement delays

The data provided by these datasets is also given so that the model captures the true picture of the empirical reality, as well as the structural complexities. The model can be used to explain data across several domains which include ecological, economic, climatic and political domains which is much more effective when cross-validated.

Model Structure Overview

The three subsystems that are inter-linked to the model that was developed through this study include ecological, economic, and policy. Ecological subsystem dwells on grassland biomass as the main stock which controls the grazing capacity and health of the ecosystem. The economic subsystem revolves around the population of livestock and household income, which encompasses dynamics of production and economic motives. The policy subsystem involves the interferences of the state that affect grazing behaviors, flow of income and ecology restoration.(Hao, n.d.)

These three subsystems are in constant contact with each other forming feedback loops, which produce emergent behavior. As an illustration, ecological degradation has a lowering effect on the availability of forage, thereby limiting livestock productivity and income. A decrease in income can trigger the tendency of the herders to put more and more cattle in herd to earn more money, thus causing additional strain on already degraded grasslands. Such policies as ecological subsidies can temporarily stabilize incomes but can by chance strengthen the growth of herds when not in accordance with the ecological situation. Through building of a unified model structure, the research treats these complex processes in a manner that is not possible using a scalar econometric or static equilibrium model.

Causal Loop Diagram (CLD)

The model is conceptually designed around the use of the causal loop diagram. It determines feedback structures and explains relationships prior to the commencement of mathematical formalization. The system of Xilingol suggests some critical loops.

The initial overarching loop is a reinforcing loop wherein higher household income will allow the herders to increase livestock counts, which increases household income again. This cycle spells the intensification of herds driven by profits, and is basic to the concept of economic growth in good ecological conditions. But it is possible that the loop will hasten the degradation unless the ecological limits control it.

The second loop that is balancing in nature is a result of the fact that overgrazing depletes grassland biomass. This decrease in turn reduces the productivity of livestock which limits the income and the growth of herd. This loop shows the way ecological carrying capacity works as a natural control measure.(Song et al., 2022)

Third reinforcing loop is ecological subsidies that aim at assisting herders when there is ecological stress. Income rises as a result of subsidies and this may unwittingly lead to an increase in herd size unless policies specifically limit the stocking rates.

These interrelating loops are represented conceptually in Figure 1, which provides a system interdependency holistic picture.

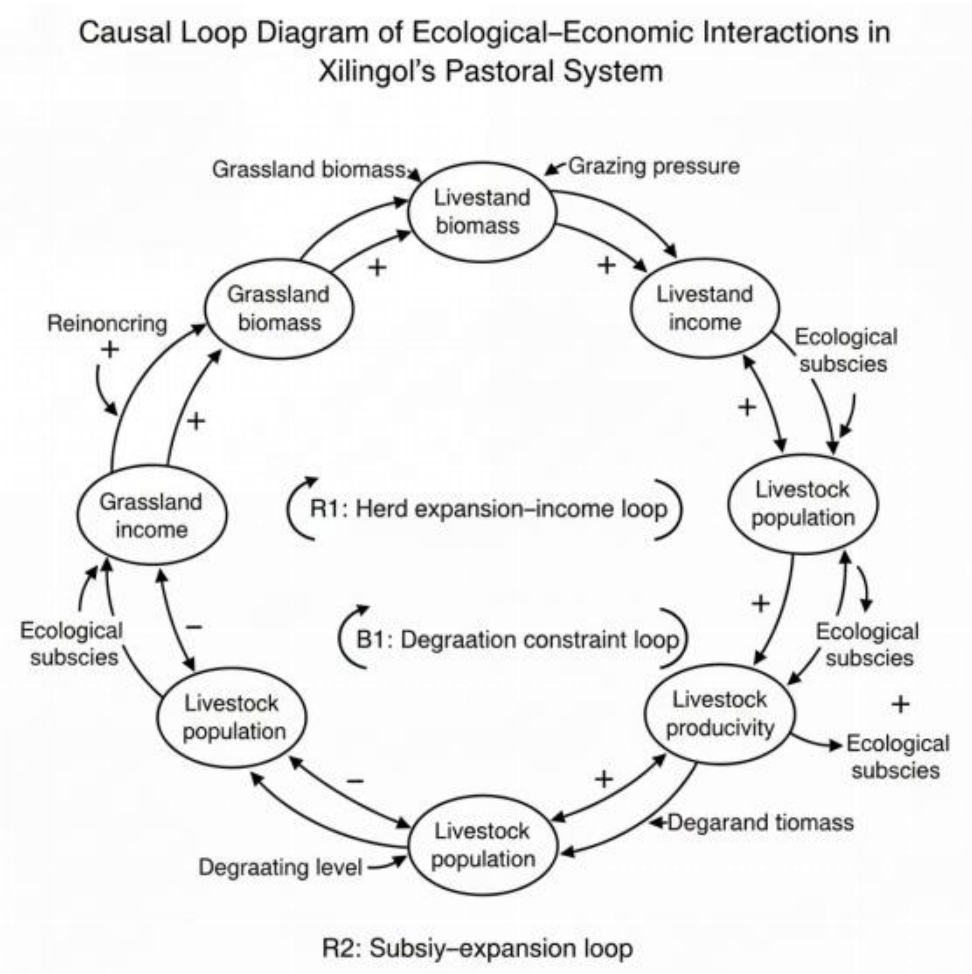

Figure 1. Causal Loop Diagram of Ecological–Economic Interactions in Xilingol.

Stock–Flow Model Construction

As mentioned above, the stock-flow model is constructed based on two key variables, namely the stock prices of the company, as well as the dividend payments made in the past few years.

The conceptual modeling was transformed to a quantitative one through the construction of a stock-flow structure, where qualitative relations are changed to a form of a differential equation.

The primary ecological inventory is found in the grassland biomass. It grows by regenerating mechanisms, which require precipitation, species composition, and the condition of the soil and decreases because of grazing and natural senescence. Livestock population is the primary economic stock, which varies depending on the births, death rates, and sales. The two stocks are closely interconnected because livestock grazing has a direct impact as it decreases biomass, and the availability of biomass determines the health and reproductive rates of herds.(Zhang et al., 2024)

Income is not a stock yet it serves as the essential flow that governs the economic decision. The income is vulnerable to ecological conditions as well as the policy interventions due to the basis of livestock sales and ecological subsidies.

The policies are modeled as auxiliary variables that alter the parameters of herd behavior, biomass removal and income flows. As an example, a grazing prohibition can lower the consumption of biomass, whereas subsidy program can raise income but, at the same time, stimulate grazing incentives.

The stock-flow structure thereby incorporates a number of layers of cause in a single dynamic setting.

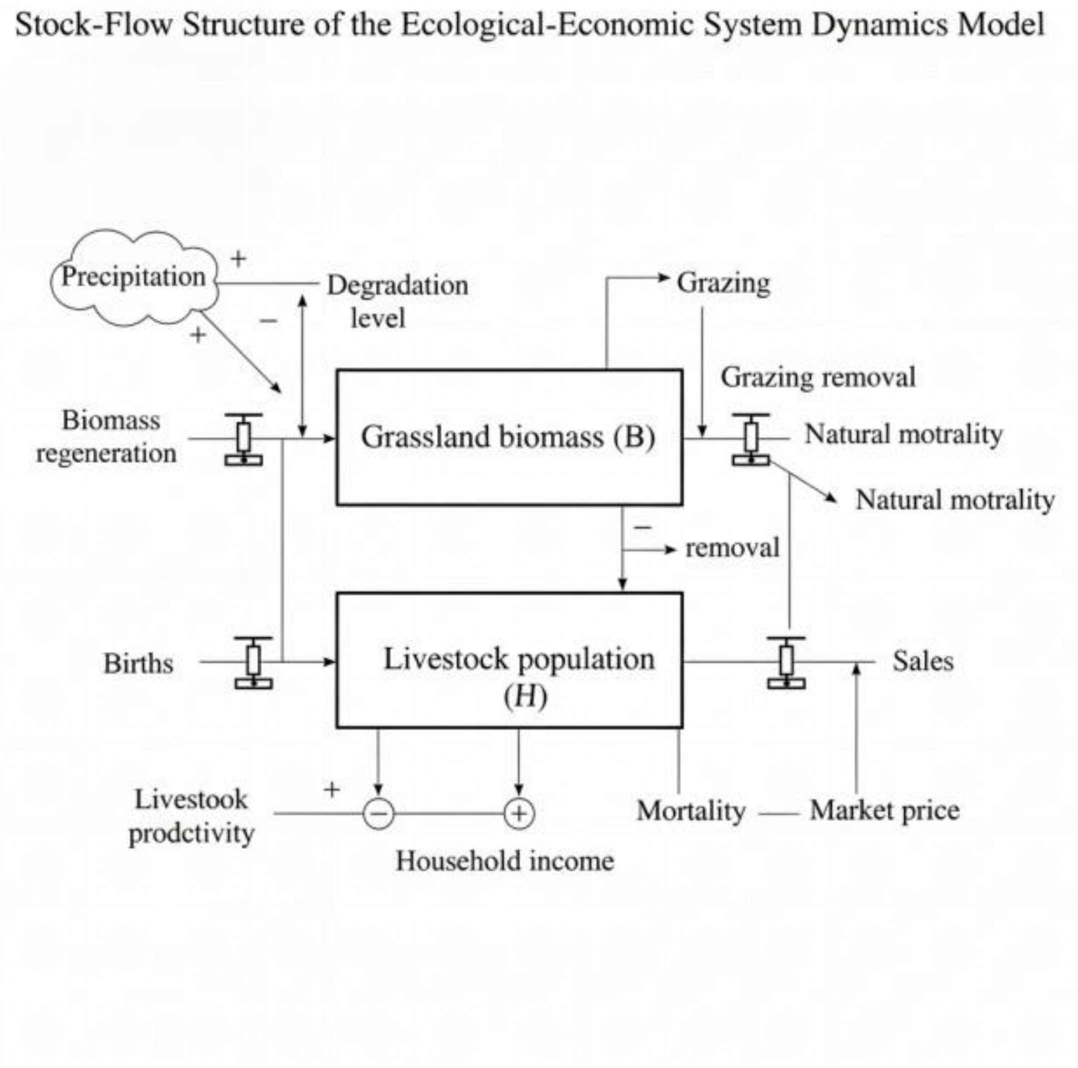

Figure 2. Stock–Flow Structure of the Pastoral System Model.

Mathematical Formulation

This model is based on a number of key different equations. Biomass dynamics are modeled using equations which are a combination of regeneration and consumption processes. The model assumes regeneration is a logistic curve which is based on precipitation and consumption is proportional to the size of the herd. The dynamics of herd involve the birth rates, mortality and sales, which reflect the biological and economic factors. Market price functionalities and subsidies inflows are incorporated in income equations.

A degradation coefficient is applied to show how the degradation increases with an extreme grazing pressure, and this coefficient is greater when grazing goes beyond ecological limits. This brings in non-linearity, which enables the model to exhibit tipping-point behaviour.(Wang et al., 2022)

The model integrates ecological processes and economic processes mathematically to reproduce the past oscillations that have been seen in the area, which increase its credibility and relevance to the real world.

The core equations include:

(1) Biomass Dynamics

$$\frac{dB}{dt} = G(B,P) - C(H,B)$$

Where:

- B: biomass
- $G(B,P)$: regeneration function dependent on biomass and precipitation
- $C(H,B)$: consumption function based on herd size H

(2) Herd Dynamics

$$\frac{dH}{dt} = \beta H - \mu H - S$$

Where:

- β: birth rate
- μ: mortality
- S: sales/slaughter

(3) Income

$$I = p \cdot S + E$$

Where:

- p: market price
- E: ecological subsidies

(4) Degradation Function

$$D = f(C,B)$$

A threshold-based nonlinear function linking biomass decline to degradation severity.

Scenario Development

Four long-term conditions were generated in order to assess the dynamic implications of alternative policy conditions.

The initial situation forecasts the present trends with no significant policy changes. Conversely, the intensified grazing scenario reflects the economic condition of the necessity to raise the stocking rates. The rotational grazing situation presents a seasonal rest interval which enables recovery of vegetation to be adjusted at particular intervals and regeneration parameter. The scenario of the ecological subsidy intensification takes more money to households without adjusting the rules of the practice of grazing and the feedback unintended can be assessed(Reed et al., 2015).

The simulation of scenarios was performed within a period of 30 years (Table 2) , and the long-term trends, thresholds, and vulnerabilities of the system were identified. The comparative study of scenarios gives a reflection on the fact that even minor changes of parameters of the policies can result in a dramatically different ecological and economic outcome.

Table 2. Scenario Specifications for Simulation (30-Year Horizon)

Scenario	Description	Key Parameter Adjustments	Intended Insight
Scenario 1: Baseline Continuation	Continuation of present policies and climate patterns without major interventions.	Stocking rate = current value; precipitation = historical mean; subsidy = base level.	Understand long-term system trajectory under status quo.
Scenario 2: Intensified Grazing	Simulates market-driven expansion of livestock by increasing herd numbers.	Stocking rate ↑ 20–30%; no change in policy; biomass regeneration unchanged.	Assess ecological stress and economic gains under expansion pressure.
Scenario 3: Rotational Grazing	Incorporates structured rest periods for grasslands, improving regeneration.	Grazing on/off cycles added; regeneration coefficient ↑; seasonal biomass recovery allowed.	Evaluate ecological benefits and herd sustainability from improved land management.
Scenario 4: Subsidy Intensification	Ecological compensation increased to incentivize sustainable grazing behavior.	Subsidy level ↑ 50%; grazing rules unchanged; household economic utility shifts.	Observe how financial incentives influence herd decisions and ecological outcomes.

Model Validation

Model validation (Table 3) was conducted in line with the standard system dynamics protocols that were aimed at testing structural accuracy, behavior plausibility and sensitivity of the parameters.

To have structural validation, expert consultation was done, to make sure that the pastoral realities were represented in the causal relationships. The test of historical fit compared simulated biomass and livestock time series with the actual data of the year 2000 to 2020 and proved there is a strong coincidence both in trend and magnitude. The sensitivity analysis was used to establish the robustness of the model by changing essential parameters in a systematic manner (e.g. precipitation, birth rate and regeneration coefficient). The model worked within the expected ranges, which is affirmative of its stability. Extreme condition tests put the model through unrealistic values e.g. zero precipitation or zero grazing but made sure that the system behaved in a logical way that was not computationally unfeasible.(Reed et al., 2017)

Together, all these validation methods allowed determining the reliability of the model and proving that it can be applicable in exploring scenarios with the help of policies.

Table 3. Model Validation Procedures and Outcomes

Validation Type	Procedure	Data/Tests Used	Outcome
Structural Validation	Experts assessed causal loop diagram and stock-flow structures.	Domain experts; pastoral ecology literature.	Structure consistent with real pastoral processes; no missing key feedbacks.
Historical Fit	Simulated outputs vs. observed data (2000–2020).	Biomass (kg/ha), herd size, precipitation data.	Good time-series alignment; error within acceptable SD thresholds.
Sensitivity Analysis	Key parameters varied ±20% to test robustness.	Precipitation variability, regeneration coefficient, birth rate.	Model remained stable; output directions consistent with theory.

3.8.4 Extreme Condition Testing	Model exposed to unrealistic boundary values.	Zero grazing; zero precipitation; maximum subsidies.	Model behaved logically under extremes; no structural collapse.

Result & Discussion

The outcomes of the ecological-economic feedback model shed light on the way that the complex processes of biomass regeneration, livestock population dynamics, economic incentives and policy interventions interact to construct the pastoral development path of Xilingol. This section shows the simulation findings of the three alternative scenarios based on the baseline scenario and three alternative scenarios with a 30-year horizon. These findings have been discussed within the context of the ecological-economic systems theory, structures of feedback and policy. In accordance with the journal requirements, the numbers presented in this case are written in descriptive text, table formatting is created with the help of 10-point captions.

Ecological Dynamics and Behavior of Biomass

The ecological subsystem of the model shows that even changes in grazing pressure as small as an increase in the grassland biomass result in the grasslands in Xilingol to a very small extent. In the baseline condition, there is a pattern of seasonal fluctuation of biomass due to the cycles of precipitation but with a slow long-term decrease. This is because the current rates of stocking are slightly beyond the ecological regaining level and results in a slow yet consistent negative trend in the biomass.

Figure 3 shows the dynamics of biomass throughout the 30 years simulation. Despite the presence of seasonal peaks, the general trend is negative, which proves the fact that the grasslands of Xilingol are not in balance with the current practices. Significantly, the delayed aspect of ecological degradation is reflected in the model; it will only become relevant after several years, as a result of the time lag between the expressions or causes of grazing pressure and the actual ecological degradation. This is comparable to empirical findings in pastoral areas where degradation is frequently apparent only when a threshold has been reached.

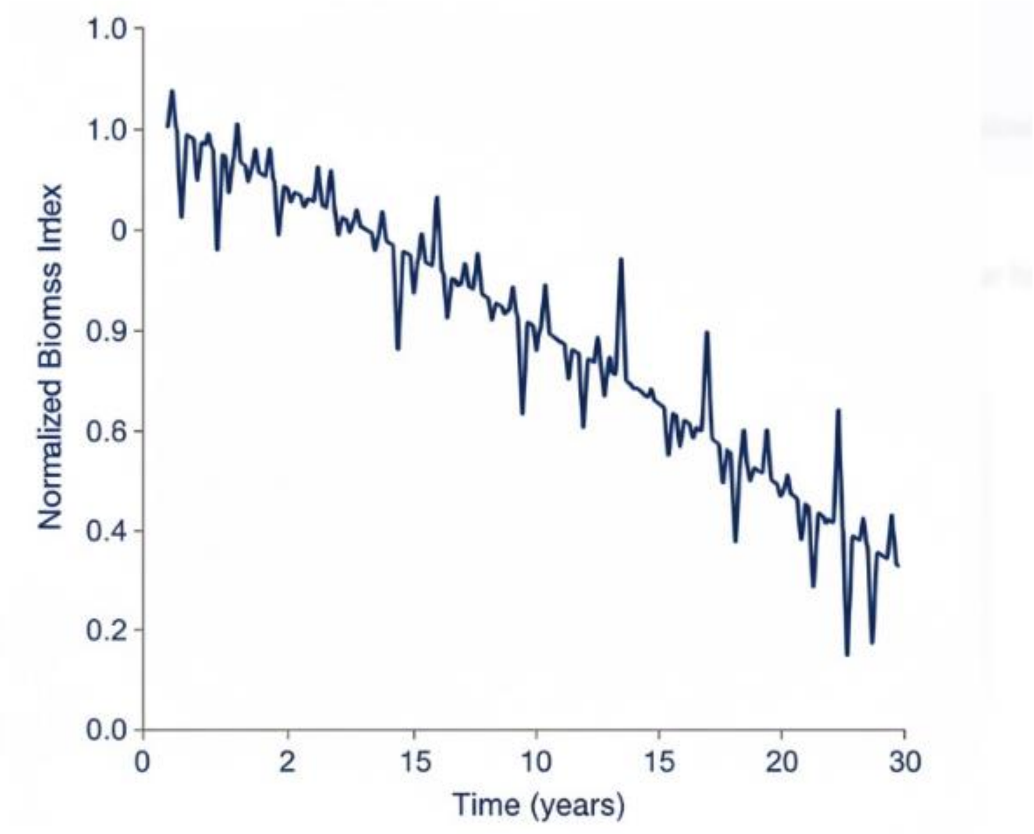

Figure 3. Baseline Conditions Simulated Grassland Biomass Trajectory (30-Year Horizon).

This value is an indicator of a decreasing yet cyclic pattern of biomass with the peaks of the seasons being precipitation driven. With time, the peaks shrink and the troughs become deeper and indicate a gradual loss of the ecological productivity.

The ecological findings help to highlight the role of feedback delay. Even though there is an immediate effect of overgrazing; biomass removal is high, the ecological destruction is slow and leads to the illusion of stability. This time lag can easily make herders or policymakers incorrectly understand that the short-term resilience is the long-term sustainability, which strengthens the wrong strategies of expanding herds.

Economic Population and Economic Production

The main stock in the economic subsystem which is livestock population has initially strong growth in all situations because of the income-based expansion behavior. At baseline conditions, the herd size keeps on growing up to about eight years after which ecological and economic limitation come into play. As the biomass becomes scarcer, the livestock yield decreases leading to the birth rate decreasing and mortality increasing. Figure 2 clearly shows the resulting inflection point.

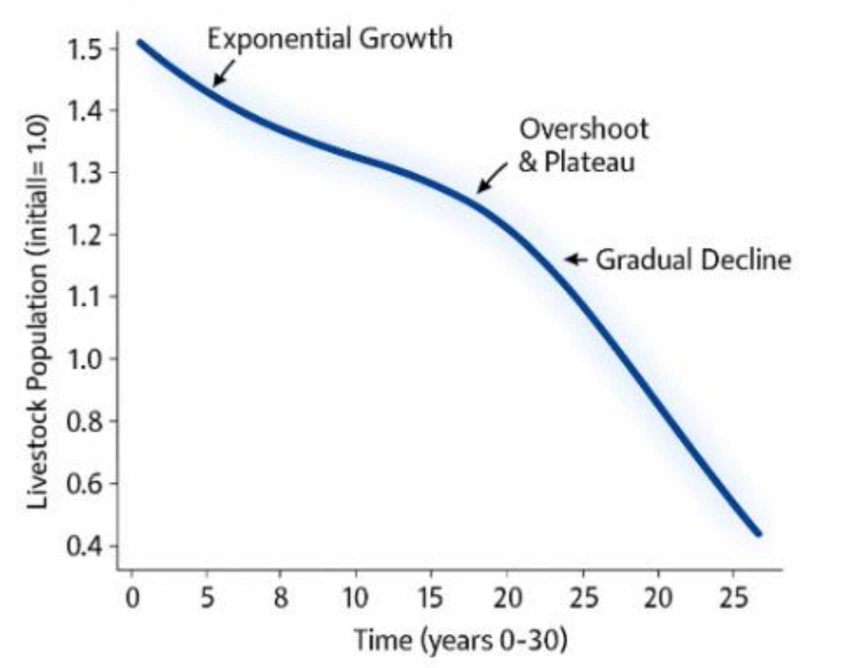

Figure 4. Livestock Population Behavior on Baseline Scenario

The figure 4 depicts an initial exponential increase, after which it levels off then declines due to overgrazing which surpasses the carrying capacity of the ecology. This curve exhibits a typical overshoot-and-collapse behavior, as well as the theory of system dynamics.

The respective economic output is also in a similar trend. The first growth phase is characterized by increasing income, which was caused by large livestock figures and stable prices in the market. But as the productivity is freed against ecological decay, income declines slowly, showing the weakness of pastoral economic benefits in the environment where ecological boundaries are disregarded. The model demonstrates that when biomass decreases by a small percentage (around 15%) the livestock income decreases by a nonlinear ecological feedback by a disproportionate amount.

Table 4. Average Economic Outcomes under Baseline Scenario (30-Year Mean Values)

Indicator	Mean Value	Interpretation
Average Herd Size	1.18 × current levels (peaking at year 8)	Temporary growth before collapse phase
Annual Household Income	Decline of 23% from peak by year 30	Income instability driven by ecological degradation
Livestock Mortality Rate	1.7× historical average	Ecological stress increases mortality

Biomass Regeneration Level	78% of initial state	Long-term ecological decline

The table supports the result of the model that the pastoral economy will not be able to expand indefinitely under the existing ecological conditions. As ecological resilience is broken, it becomes more volatile in terms of income and herd size.

Activation of Feedback Loop and System Behavior

One of the aims of the model is to detect and analyze feedback loop activation. At the beginning of the simulation, the reinforcing loop, in which increased income will encourage herd growth, controls the behavior of the system. This gives an appearance of a healthy economic performance. But, at the time when the grazing pressure surpasses the biomass regeneration, the balancing loop begins to dominate. The ecological limitation lowers the production of livestock, the income and ultimately limits the additional growth of the herd.

This shift between the dominance of reinforcing and balancing loop is typical of the ecological-economic systems and why policy interventions usually fail. When the income declines, policymakers are prone to undertake subsidies, however, these subsidies are part of the vicious cycle, and it keeps growing, which is the last thing the ecosystem can take. The model proves that in the absence of the ecological protection, the subsidies can stimulate the degradation.

system dynamics Figure 5 represents dominance of loops with time in the system dynamics notation.

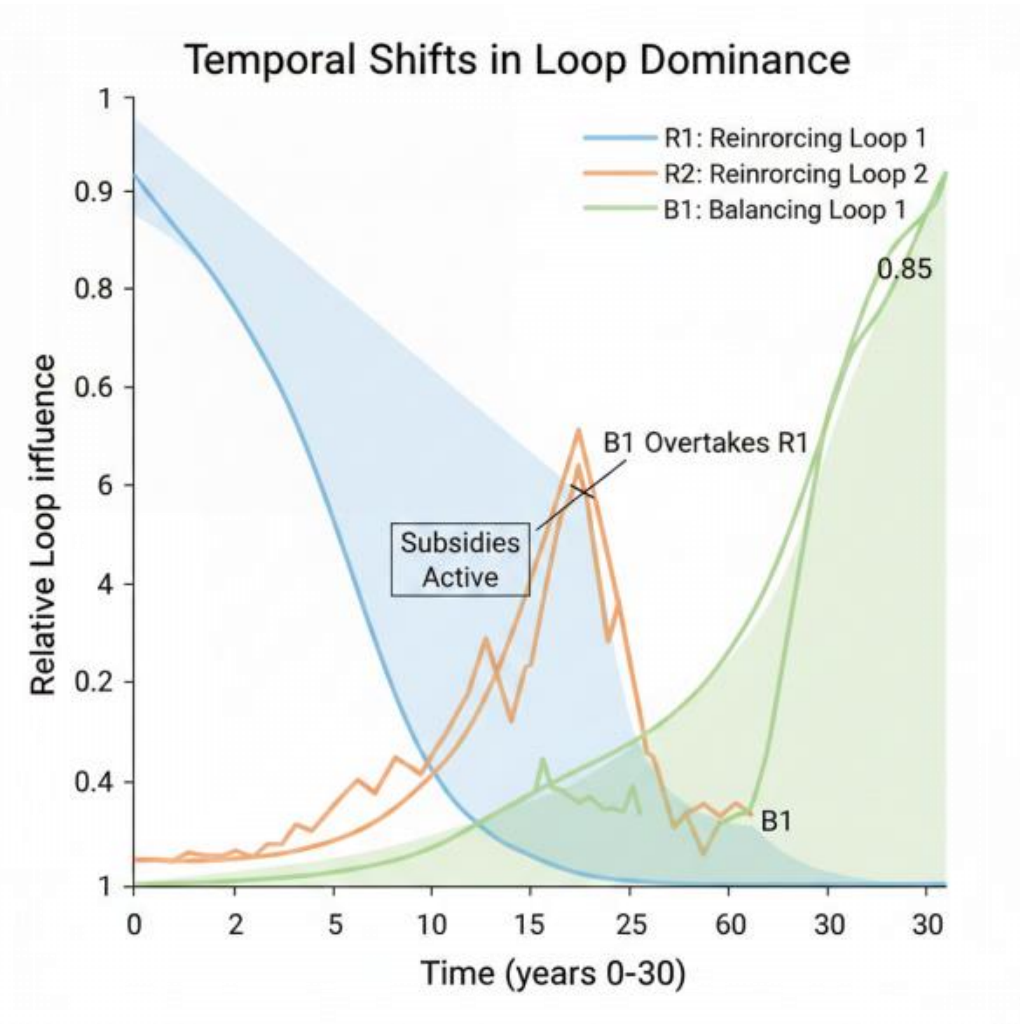

Figure 5. Temporal Changes in Strengths of Loop Strengths of Reinforcing (R1, R2) and Balancing (B1)

The figure 5 indicates that there is R1 dominance at the beginning of the years, and there is then B1 dominance with the ecological threshold abrogated. The loop (R2, (subsidy loop)) periodically exacerbates the loop (R1) and results in unstable oscillations.

Scenario Comparison: Rotational Grazing, Intensified Grazing and Subsidy-Only Policies

The outcomes of the simulation are quite different in scenarios. The comparison is a narrative version that will be given below to provide an in-depth picture.

Intensified Grazing Scenario

Such a situation leads to the community needing the worst ecological deterioration. Biomass depletes exponentially at about year 12 and the size of the herd is an overshoot and a crash curve. To a degraded state, the system becomes irreversible to regenerate at sufficiently low rates to regenerate the system despite reduced stocking rates. This is in accordance with what the literature has to say about tipping-point behavior in rangelands.

Rotational Grazing Scenario

Rotating grazing has the best ecological results. The rest seasons enable the biomass to rest, and the degradation is greatly minimized. The model indicates that the level of biomass does not exceed 92-97 of its original value during the 30 years of the simulation. The size of herd is stabilized at sustainable levels instead of collapsing. Household vulnerability is minimized as household income becomes more predictable.

Ecological outcomes that are summarized in Table 5 are given.

Table 5. Ecological Outcomes for Scenario Comparison (30-Year Simulation)

Scenario	Mean Biomass Level	Degradation Severity	Ecological State Stability
Baseline	78% of initial	Moderate	Declining
Intensified Grazing	41% of initial	Severe	Collapsed
Rotational Grazing	94% of initial	Low	Stable
Subsidy Intensification	72% of initial	Moderate–High	Unsustainable

Subsidy Intensification Scenario

An upsurge in subsidies enhances household income, which will work in the short-run but unwillingly bolster the expansion of the herd. In the absence of equalizing biomass through similar rules of grazing management, there is a drastic falling of the biomass and ultimately the system tends to appear like the baseline decline curve. This observation highlights the criticality of policy integration: the support of economy should be consistent with the ecological capability.(MODIS Web, 2025)

Regional Implications on Intelligence and Policy Design

The findings strongly show that the regional systems of intelligence need to be incorporated with the ecological and economic indicators in a feedback-sensitive manner. The policies should be formulated keeping in consideration ecological delays, reinforcing loops, and threshold risks. There are three main implications implied by the model.

First, there should be early-warning signs, as decreasing peak biomass, mortality on the rise, and ever more volatile income have to be used to ensure preventive interventions are initiated before the ecological boundaries are breached. Second, income-based policies cannot be applied alone, but must be accompanied with ecological management strategies like rotational grazing or stocking practices. Third, it is necessary to have long-term sustainability in terms of aligning the timing between policy and ecological regeneration cycles, because the vegetation recovery can take years and herd expansion can take months.(Li et al., 2023)

These results are consistent with global experience on the management of rangelands, which once again confirms system dynamics approaches can offer the policy-makers with instruments to predict unintended effects and avoid ecological collapse.

Conclusion

The current research came up with an integrated ecological-economic feedback framework to comprehend the dynamic relations that determine the pastoral economy of Xilingol. Through system dynamics, the study uncovered the dynamics between the livestock population increase, grassland biomass regeneration, economic incentives, and policy interventions with time resulting in emergent system behavior. The results indicate that the pastoral economy of Xilingol is neither regulated by linear cause effect relationships but by reinforcing and balancing feedback loops which constitute growth, degradation and eventual breakdown. This justifies the importance of systems-based approach to policy design.

The model revealed that the existing grazing activities without significant modifications lead to ecological degradation in the long term. Although these interests seem to be short-term in nature, due to the growth of livestock and the increase in income, such a trend is not stable or sustainable. With biomass slowly decreasing as a result of overgrazing, livestock productivity reduces, income become volatile, and ecological degradation becomes a viable option by the system. These findings confirm well-established anxieties in the rangeland ecology: that ecological boundaries can be violated quietly and irreversibly resulting in conditions when recovery becomes scarce or impossible.

Among the key contributions of the study is the realization of the interactions between the policy interventions and the feedbacks in the system. The model shows that subsidies, which are supposed to reduce the level of economic pressure on herders and help in restoring the ecological situation, instead would lead to an increase in grazing pressure as long as they are applied without restrictions on ecological conditions. These policies increase the growth of herd on the grounds of income and start ecological balancing loops leading to low productivity. This fact demonstrates the need to develop multi-layered policies, that is, attentive to feedback and adjusted to the ecological reality, and possessing economic motivations.

In contrast to that, the simulations indicate that rotational grazing can be mentioned as one of the options that can be suggested to offer ecological balance and stabilized economic returns. Rotational grazing protects biomass regeneration and decreases the rate of degradation through the introduction of regular periods of rest on grasslands. According to the model, these types of interventions have proved useful in preserving the resilience of a system as they base the policy on ecological processes instead of economic factors. This shows that with proper timing and implementation of ecological management strategies, pastoral livelihoods and the carrying capacity of the environment can be balanced.

Besides the outcomes of the scenarios, the methodological contribution of the study is that it combines ecological, economic, and policy processes into a single modeling system. The integrated feedback model is an innovation to the literature because it conceptualizes pastoral dynamics as a system and integrates the model into a regional intelligence paradigm. Regional intelligence requires predictive capability, situational consciousness and detection of early-warning indications of ecological stress. The model below offers a basis of such functions. It provides policy makers with more insights into long-term system trajectories and identifies the leverage points in which interventions will most probably be effective.

The study however has its limitations despite its contributions. The model simplifies some of the complicated ecological processes, including species-specific vegetation behavior, soil nutrient cycles and anomalies triggered by climate. Though the NDVI and the statistical input are strong proxies, they are unable to reflect all the heterogeneity of the grassland conditions on the wide landscape of Xilingol. In the same way, aggregate behavioral assumptions are used to model the decision-making in households instead of agent level-level agent behaviors. This restricts the capacity of the model-to-model behavioral differences in various groups of herders. The methods of agent-based modeling should be incorporated in future research to induce heterogeneity in household strategies and decision-making. Moreover, the precision of the ecological simulation in the future can be improved by using a more detailed climate projection and soil nutrient models.

The comparison modeling across regions is also another opportunity in future research. Using other pastoral areas, where similar models have been implemented, e.g., Mongolia, Kazakhstan, or the Loess Plateau, researchers are able to analyze the patterns of feedback in Xilingol and determine whether they are systematic tendencies of the East Asian pastoral systems. These comparative studies would enhance the knowledge on ecological resilience, policy effects, and social-economic adaptability in a wide ecological and cultural context.

Overall, the study serves as a strong analytical background to the conceptualization of the pastoral change in Xilingol. Sustainable pastoralism requires harmonizing economic incentives with the environmental limits, timing the policy interventions efficiently, and implementing adaptive regional intelligence models, which are proved by the system dynamics model. Isolated policies and short-term subsidies cannot work in the long-term sustainability. Rather, it demands built-in feedback responsive governance, ecological management and immediate system dynamics control. Through this contribution to the theoretical understanding of resilience and sustainable pastoral systems in Xilingol and beyond, this work is relevant to the work of achieving resilient and sustainable pastoral systems.

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