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# Simulation-Based System Modeling of Grazing Land Management for Beef Cattle Development in East Luwu, Indonesia

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## Abstract

Significant population growth has increased demand for beef, while domestic production lags. Poor grazing land management and cattle population pressure remain major constraints, underscoring the need for sustainable solutions. This study aims to develop a system dynamics model and formulate grazing land management strategies to support sustainable beef cattle farming in East Luwu Regency, as one of the cattle production centers in South Sulawesi with extensive but increasingly degraded grazing lands. Conducted from May to July 2025, the model integrated grazing land and cattle population dynamics through causal loop and stock-flow diagrams, while the analytical hierarchy process (AHP) was used to prioritize management strategies. The model reveals that cattle population dynamics are primarily influenced by forage availability, cattle purchases, and birth rates, while grazing land depends on water supply, soil quality, and land availability. From 2020 to 2024, the average grazing land area was 3,013.72 ha with a grass regeneration rate of 1.11 kg $ha^{-1}$ $day^{-1}$ and a declining maximum carrying capacity (3,075 ind $ha^{-1}$ $year^{-1}$). During the same period, the cattle population averaged 20,411 heads but declined annually by -1,036.5 heads, with a feed ratio of only 0.03% per day, highlighting the urgent need for an effective management strategy. The AHP results indicate that the Integrated Feed Management and Population Control (IFM-PC) strategy achieved the highest score across sustainability criteria, while the reduced stocking rate (SR↓/ha) ranked lowest. This study concludes that grazing land and cattle populations in East Luwu are undergoing considerable degradation, and implementing IFM-PC is crucial for long-term sustainability.

**Keywords:** analytical hierarchy process (AHP); causal loop diagram (CLD); meat production; stock flow diagram (SFD); sustainable agriculture

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## INTRODUCTION

The world's population is projected to increase to nearly 10 billion by 2050 (United Nations, 2017). At the national level, Indonesia's population is approximately 275.77 million and is expected to grow significantly to around 319 million by 2045 (Statistics of Indonesia, 2022a). This rapid population growth directly impacts the rising demand for food, including animal-based products such as beef. Historically, Indonesia has relied on the importation of breeding cattle since

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the 1990s to meet domestic beef demand. This marks a shift from its earlier status as a beef-exporting country until 1978 (Rey, 2022). These facts reflect a growing national demand for beef that has outpaced the country's domestic production capacity. Thus, enhancing local livestock systems becomes a national imperative to reduce import dependency and improve protein self-sufficiency.

In 2022, beef consumption in Indonesia reached 2.61 kg per capita per year, averaging approximately 6 g daily. Given the country's large population, the national demand for beef is estimated to exceed 670,000 tons annually, equivalent to approximately 3.4 million head of cattle. However, domestic production has only managed to supply about 403,668 tons (roughly 60% of demand), or the equivalent of 2.4 million head of cattle. This results in a supply deficit of around 1 million head of livestock (Statistics of Indonesia, 2022a). Such a shortfall presents a significant challenge to national food security, particularly in ensuring the availability and sustainability of animal protein sources for the population. Therefore, the sustainability of beef production is not only an economic issue but a strategic concern for national resilience.

East Luwu Regency, located in South Sulawesi, Indonesia, holds considerable potential for developing beef cattle farming. In 2022, the beef cattle population in the region reached nearly 30,000 head (Statistics of Indonesia, 2022b). However, the development of this sector is constrained by a lack of data concerning the condition of grazing lands, including land area, botanical composition, forage productivity, nutritional content, digestibility, and livestock carrying capacity throughout the year. In East Luwu, cattle are generally reared under a free-range grazing system, where animals depend directly on natural pastures for feed, making accurate information on grazing land conditions essential for sustainable management. Natural grazing lands are the primary feed source for ruminants such as cattle (O'Grady et al., 2024). The shrinking extent of grazing areas and limited forage availability have become significant obstacles to sustainable beef cattle farming (Hasan et al., 2016). Despite its potential, East Luwu lacks a comprehensive system for evaluating and managing grazing lands effectively, creating a critical knowledge and management gap. The regency has approximately 3,013.72 ha of grazing lands on average over the last five years, which serves as a key resource for free-range cattle production (2020 to 2024 data).

In agro-industry, the development of system models today must go beyond focusing solely on economics and sustainability while still considering the increasingly urgent concepts related to the Sustainable Development Goals (SDGs) (FAO, 2016). One pressing issue is the competition for land use between food crops and cattle feed crops, where feed crops have not yet become a priority in land allocation (Sema et al., 2023). In this context, applying sustainable development paradigms in the agro-industry sector becomes crucial, especially in addressing the challenges of climate change, which impacts food security. Sustainable development emphasizes the efficient use of natural resources, including the management of grazing lands, to support the sustainability of beef cattle farming (Tedeschi et al., 2024). System-based solutions are thus essential to balance ecological, economic, and food security dimensions within regional livestock development.

Sustainable grazing land management involves interacting with animals, plants, soil, and other environmental components. Proper management considers pasture quality, livestock density, soil conditions, and the quantity and quality of available forage (Ibrahim and Usman, 2021). However, a holistic and integrated approach to grazing land management requires in-depth analysis and the use of data-driven models to evaluate various management scenarios that can support the sustainability of beef cattle farming (Jones et al., 2017). Climate change, which affects grazing land conditions, can disrupt the stability of forage production, impacting the sustainability of beef cattle production. Therefore, adaptive management of grazing lands in response to climate change is essential to maintaining the sustainability of Indonesia's beef cattle sector. Despite existing pasture and livestock management studies, limited research has combined system dynamics with field-based grazing land analysis at the regional level. This creates a novel entry point for this study.

To address the imbalance between national beef demand and production, a data-driven and systems-based approach is needed to map the issues comprehensively (Hilmiati et al., 2024). One promising approach is developing a livestock management application utilizing system dynamics modeling. This model allows stakeholders to simulate a range of variables, including livestock population, beef consumption, productivity, and the long-term effects of specific policies on beef production outcomes. These simulations generate alternative strategy scenarios, such as increasing breeding cattle populations, improving feed distribution efficiency, and implementing subsidies (Xue et al., 2023). As a result, decision-making in livestock management can be more targeted, adaptive, and evidence-based, supporting the sustainable achievement of national food security. System dynamics thus offers a practical and replicable method for transforming complex livestock-environment interactions into actionable policy alternatives.

Currently, the agro-industry sector faces significant challenges in increasing productivity while simultaneously reducing environmental impacts, which drives the need for sustainable intensification in production (Springmann et al., 2018). Research that applies system dynamics models in the management of grazing lands can provide valuable insights into the interconnections between various factors affecting the sustainability of beef cattle farming. Jones et al. (2017) state that the complex interactions between animals, plants, and the environment within agro-industrial systems require process-based models. Therefore, applying a holistic and integrated model is essential to formulate effective grazing land management strategies that support sustainable beef cattle farming in the region. This study contributes a novel system dynamics-based framework tailored to the specific biophysical and policy context of East Luwu, aiming to bridge empirical data gaps and improve decision-making for sustainable beef cattle development.

## MATERIALS AND METHOD

### Duration and study area

This study was conducted in East Luwu Regency, South Sulawesi Province (Figure 1), from May to July 2025, using data from the last five years (2020 to 2024). The sampling locations were determined using purposive sampling with criteria including topography, climate conditions, and dominance of cattle grazing activities, based on data from Statistics of Indonesia (2022b) and Meteorology, Climatology, and Geophysics Agency in 2023. Geographically, the study area is situated between 119°28’56’’ to 121°47’27’’ E and 2°03’00’’ to 3°03’25’’ S. The area’s topography is predominantly hilly, with an average elevation of 96.36 m above sea level (m asl) and slope classified into three ranges: 15 to 25%, 25 to 45%, and > 45%.

### System dynamics model

The system dynamics model was developed following the steps outlined by Grant (1998), which are: (1) identification of the problems, objectives, and key variables; (2) conceptualization of the model through the development of box-and-arrow diagrams to represent the flow and relationships between elements; (3) specification of the model, including the formulation of mathematical equations and quantification of each variable; (4) model evaluation through the comparison of simulation results with actual conditions to test the model’s

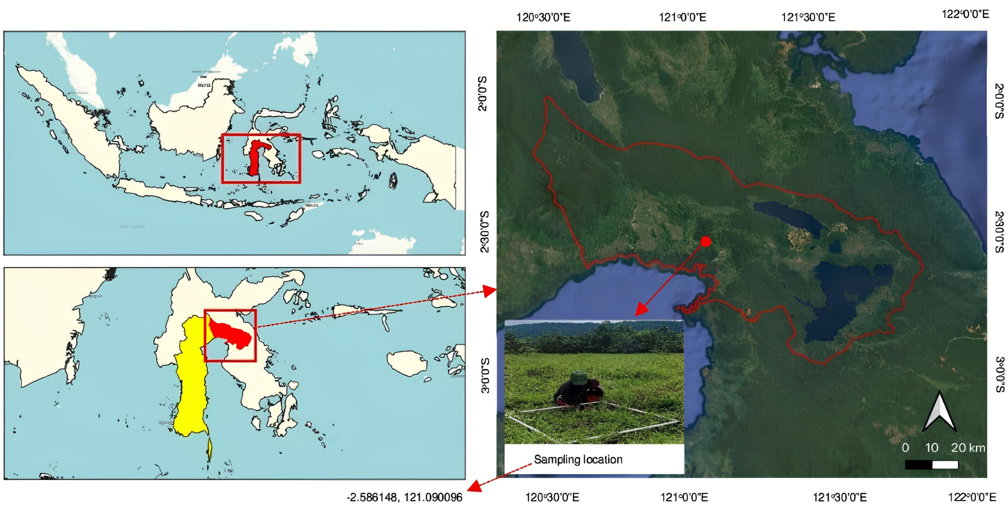


Figure 1. Map of study area (East Luwu, South Sulawesi Province, Indonesia)
Source: SAS Planet, WAGS CGS (1984), authors’ analysis based on Statistics of Indonesia (2022b) and Google Earth (2023)

validity; and (5) application of the model in the form of policy scenario formulation. The model construction is based on causal loop diagrams (CLD) and stock flow diagrams (SFD), representing the dynamic interrelationships among the variables in the system.

*Grazing land dynamics*

The development of the model is expected to provide an overview of habitat carrying capacity for supplying feed to cattle. The habitat carrying capacity for cattle feed consists of several variables, including the total area of grazing land, the area designated for cattle grazing, forage productivity, and the carrying capacity. The feed capacity, derived from the maximum carrying capacity of the grazing land during each grass regeneration period, can be calculated using Equation 1.

$$TGR = GR + RR \tag{1}$$

Where, TGR = total of grass regeneration; GR = growth rate; RR = recovery rate.

The maximum carrying capacity is the product of the pasture carrying capacity coefficient per hectare and the available grassland area, as expressed by Equation 2.

$$MCC = (GA \times CC \text{ per are}) + TGR \tag{2}$$

Where, MCC = maximum carrying capacity; GA = grassland area; CC per are = carrying capacity per are.

The grass regeneration period refers to the duration associated with the increase in forage growth quantity. This increase is linearly related to Equation 3.

$$Y = 35 + 80X \tag{3}$$

Where, Y = relative increase in feed quantity; X = forage.

Furthermore, the relative increase in forage quantity can be calculated using Equation 4.

$$RIFQ = \frac{F}{MCC} \tag{4}$$

Where, RIFQ = relative increase in feed quantity; F = forage.

The grass regeneration period provides a quantitative input to the maximum carrying capacity, with the forage calculation formula expressed as Equation 5.

$$Forage = MCC + TGR \tag{5}$$

*Livestock population dynamics*

Livestock population dynamics include variables such as population growth rate, birth rate, death rate, exponential growth, and intrinsic growth rate. The population growth rate is the difference in the number of individuals at different time points, divided by the time interval over which the population changes. The birth rate is calculated as the ratio of the number of individuals born in a year to the total population in that year, using Equation 6 (Gotelli, 1995).

$$b = \frac{B}{N} \tag{6}$$

Where, b = birth rate; B = number of births; N = total number of existing cattle populations.

The mortality rate is calculated as the ratio of the number of deaths to the total population over a specific period using Equation 7 (Gotelli, 1995).

$$d = \frac{D}{N} \tag{7}$$

Where, d = mortality rate; D = number of mortality.

The population growth rate can be calculated based on the change in the number of individuals within a specific time interval using Equation 8 (Gotelli, 1995).

$$PGR = \frac{DN}{Dt} \tag{8}$$

Where, PGR = population growth rate; DN = the change in the number of individuals in a population; Dt = time interval change.

Exponential growth can be calculated from the difference between the birth rate and the mortality rate. The initial equation is Equation 9 (OpenStax, 2022).

$$\frac{DN}{Dt} = b - d \tag{9}$$

Since the number of births and mortality depends on the population (N), where B = bN and D = dN, the derivative of the equation becomes Equation 10 (OpenStax, 2022).

$$\frac{DN}{Dt} = bN - dN = (b - d) \text{ x } N \tag{10}$$

The intrinsic growth rate (r) is the difference between the birth and mortality rates, i.e., r = b–d. Since the cattle population in nature is highly limited and constrained by the carrying capacity of the environment (K), the exponential population growth can be expressed as Equation 11 (OpenStax, 2022).

$$\frac{DN}{Dt} = rN \times \frac{K - N}{K} \quad (11)$$

Subsequently, the beef cattle population is calculated using Equation 12 (Odum and Barrett, 2004).

$$P = (NIP + b) - (d + Qs) \quad (12)$$

Where, P = current beef cattle population; NIP = net increase in population; Qs = sales quantity of cattle.

Furthermore, population growth is also influenced by proportional factors related to the sex ratio and feed adequacy, which is measured through the feed ratio. The feed ratio is calculated using Equation 13.

$$FR = \frac{FReq}{NC} \quad (13)$$

Where, FR = feed ratio (%); FReq = forage requirements per cattle (FU $year^{-1}$); NC = normal consumption of forage per cattle (FU $year^{-1}$).

**Analytical hierarchy process (AHP)**

An appropriate management strategy is required to balance grazing land capacity and beef cattle productivity, particularly under multiple interconnected variables. The AHP was employed to evaluate management strategies based on technical and biological criteria (Giri and Nejadhashemi, 2014). AHP provides a systematic procedure involving:

*Identification of variables and hierarchical structure development*

A four-level hierarchy was developed: Level 1 = Overall goal–optimal grazing land management for beef cattle development; Level 2 = Main criteria–grazing land dynamics and cattle population dynamics; Level 3 = Sub-criteria–for grazing land, including grass regeneration, maximum carrying capacity, relative feed increase, forage availability, total grazing area; for cattle, including birth rate, mortality rate, sales, population growth, feed ratio; and Level 4 = Alternative management strategies.

*Pairwise comparison and priority weight calculation*

Each criterion and sub-criterion were compared pairwise based on relative importance to quantify their influence on the overall objective, following the Saaty scale (1 to 9). A pairwise comparison matrix was constructed, normalized, and used to calculate priority vectors that represent the weights of sub-criteria. The consistency of judgments was assessed using the consistency index, which is acceptable if the value is less than 0.1. Similarly, alternatives were compared against each sub-criterion to obtain local weights. Aggregate scores for each alternative were then calculated by multiplying local weights by the corresponding sub-criteria weights, with the highest score indicating the most preferred management strategy.

*Consistency ratio evaluation and alternative ranking*

Determining the consistency ratio aims to evaluate the reliability of the judgments made, where the results are considered consistent if the value is less than 0.1. The consistency ratio is calculated using Equation 14.

$$CR = CI/RI \quad (14)$$

Where, CR = consistency ratio; CI = consistency index; RI = random index, is a constant derived from Saaty's (1980) table based on the number of criteria (Table 1). Conversely, the consistency index is obtained using Equation 15.

$$CI = \frac{\lambda\ max\ -n}{n-1} \quad (15)$$

Where, λ max = lambda maximum; n = number of sub-criteria.

**Data analysis**

All data were tabulated and processed to quantify the relevant parameters. The AHP analysis was carried out systematically using Microsoft Excel to determine the ranking of alternatives or management strategies. Meanwhile, decision-making related to the research problem was supported through the computer-based modelling software, Powersim version 2.1. The model was developed based on

Table 1. The value of the random index

| Matrix size | 1 to 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI value | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |

Note: RI = Random index

the CLD approach, providing a simulation-based framework for analyzing policy scenarios in managing grazing lands for beef cattle production.

## RESULTS AND DISCUSSION

### System dynamics model

The visualization of the system dynamics model, developed using the PowerSim software, is presented in Figure 2 as a CLD and Figure 3 as an SFD. These figures illustrate various inputs and the causal relationships among variables. As shown in Figure 2, the beef cattle population is positively influenced (+) by purchases, births, and forage availability, indicating that an increase in these variables leads to an increase in population. Conversely, the population is negatively influenced (–) by livestock sales and mortality, meaning that increases in these variables lead to a decrease in the cattle population. Simulation results indicated that while mortality contributed to population reduction, it was not high enough to cause a significant decline during the study period. In contrast, livestock sales had a more pronounced impact, highlighting the need to manage sales alongside natural mortality to maintain herd stability. This dynamic interaction reflects a reinforcing–balancing feedback mechanism typical in livestock population systems (Nugroho and Uehara, 2023), supporting the system dynamics framework adopted in this study.

Consistent with the findings of Isyanto and Sugianti (2016), the beef cattle population is more significantly influenced by birth rates (inflow of cattle) than by mortality rates (outflow of cattle). Their study also noted that other variables, such as grazing land area, forage availability, cattle ownership levels, and beef prices, substantially affect beef cattle population dynamics. Furthermore, as illustrated in Figure 2, forage availability and grazing land tend to decrease (–) as the cattle population increases (+). At the research site, the average grazing land area declined from 3,074.6 ha in 2020 to 2,953.5 ha in 2024, indicating a gradual reduction of approximately 4% over five years. This trend highlights that increasing cattle population and associated grazing pressure contribute to the decrease in pasture resources, supporting the need for sustainable livestock management.

Forage availability is positively influenced (+) by factors such as the extent of grazing land, quality, water availability, rainfall, and biodiversity. The grazing land area exhibits moderate to high forage quality, sufficient water sources, and a diverse plant community. Annual rainfall during the study period was adequate to support grass growth, collectively contributing to the observed positive relationship between these factors and forage availability. Conversely, it is negatively affected (–) by dry season conditions. This inverse relation is crucial in

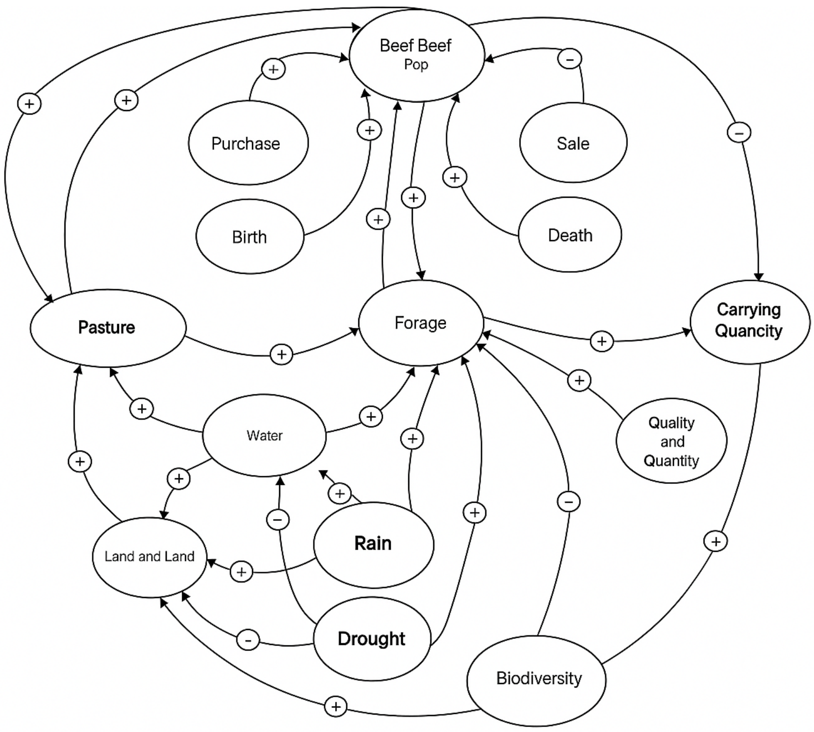


Figure 2. CLD of the grazing land management model for beef cattle farming in East Luwu Regency

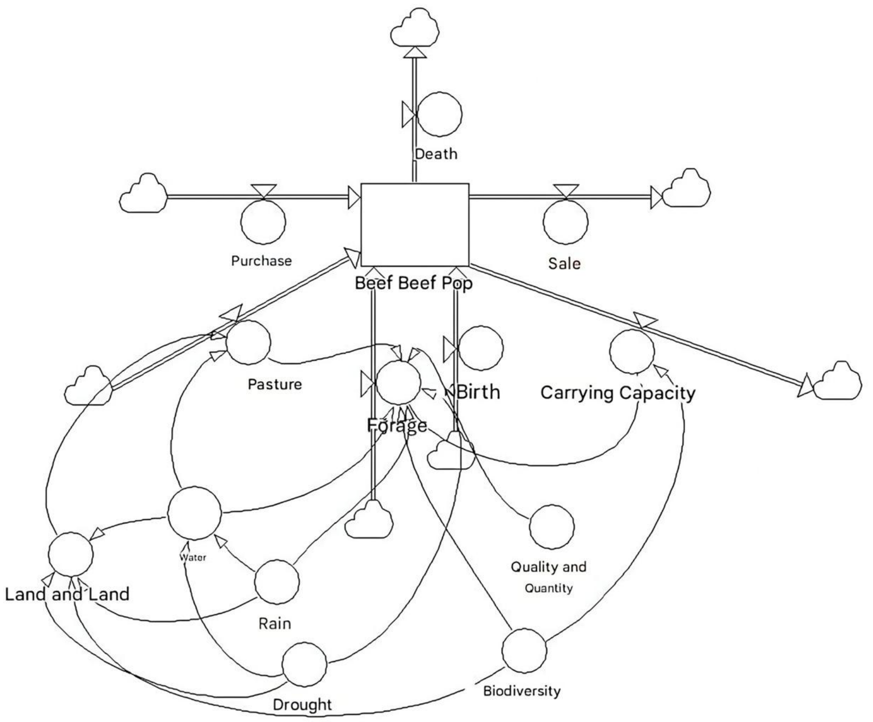


Figure 3. SFD of the grazing land management model for beef cattle farming in East Luwu Regency

dryland systems, where livestock pressure on forage triggers land degradation unless balanced by adaptive grazing management (Escarcha et al., 2018).

These results support the findings of Sulfiar et al. (2020), who emphasized the critical role of forage in cattle population dynamics and recommended allocating dedicated cultivated land for forage development. Grazing lands are positively influenced (+) by water, soil, and land area. Carrying capacity is negatively influenced (–) by cattle population and positively influenced (+) by biodiversity. Biodiversity contributes to ecological resilience and enhances forage productivity and land recovery potential (Tedeschi et al., 2024). It is also partially indicated that rainfall has a direct positive (+) relationship with both water and soil; the dry season has a negative (–) impact on soil and land; and biodiversity positively (+) affects both soil and land. These detailed outputs highlight the importance of grazing land development for optimizing cattle population sustainability. Sekaran et al. (2021) emphasized that integrated crop-livestock farming systems can improve forage availability and, in turn, support cattle population growth.

Meanwhile, the SFD analysis results, as shown in Figure 3, were used to understand, map, and simulate the system's dynamics, particularly those that change over time. Shahsavari-Pour et al. (2023) stated that system dynamics simulation models are valuable tools for considering complex combinations of variables to optimize cattle populations. The SFD consists of three main elements: stocks, flows, and auxiliary variables. Stocks represent the state or accumulation within the model; flows are time-dependent functions that determine the rate of change in stocks; and auxiliary variables are used to support the visualization and understanding of flow behavior. The SFD results reveal that changes in cattle population are directly influenced by flow variables such as mortality, purchase, and sales. Specifically, the SFD shows that these variables are exogenous, meaning they are not influenced by other variables within the system. This allows more precise identification of leverage points in the model, aligning with the system archetype of growth-limiting processes in livestock systems (Odoemena et al., 2020).

Furthermore, forage availability, carrying capacity, and the grazing ecosystem are influenced by various auxiliary variables. Forage availability is affected by several supporting factors, including water, rainfall, and the quality and quantity of the forage. Parmawati et al. (2018) emphasized that feed is a critical factor in sustaining livestock populations, with the availability of suitable land for grass growth becoming increasingly urgent. Conversely, the grazing land flow shows a strong reciprocal relationship with natural resource variables such as soil availability, land area, and water supply, which collectively influence the capacity and sustainability of grazing systems. O'Grady et al. (2024) highlighted that natural resource variables are essential for grazing land fluctuations. Similarly, Pulido et al. (2018) and Whitten et al. (2019) argued that the livestock industry can remain productive, sustainable, and profitable only when the integrity of the underlying natural capital is maintained. This reinforces the principle that environmental degradation undermines livestock system stability and must be explicitly modeled (Shahsavari-Pour et al., 2023).

Meanwhile, the carrying capacity flow is primarily regulated by fluctuations in forage availability and biodiversity. The average mortality rate was 2,635 individuals per year, while the average cattle sales rate was 806 individuals per year. These factors contributed to a negative population growth rate of -1,036.5 individuals per year, highlighting the combined impact of mortality and sales on the declining cattle population. In contrast, the forage flow emerges from the combined effects of water, rainfall, biodiversity, grazing area, and the inherent quality and quantity of the forage. A range of other variables integratively governs the flow of additional system components. For instance, water flow is influenced by seasonal variation, particularly by the dry season, rainfall, and soil conditions. Conversely, soil and land flows are shaped by the availability of water, precipitation levels, and drought periods. The interaction between water and soil flows is cyclical and mutually influential. Water flow is driven by factors such as rainfall intensity, soil moisture, and the duration of the dry season, all of which determine surface and subsurface water dynamics (Hidayat et al., 2024; Saputra et al., 2025). In turn, soil flow is influenced by water-related characteristics, including the volume and intensity of rainfall and the length of drought periods, which can accelerate erosion or lead to landform changes (Mohammed, 2025). This water-soil feedback loop is essential to understand land resilience in semi-arid cattle systems (Lei et al., 2023). Ultimately, applying the SFD enables a structural understanding of how system elements interact to produce long-term behavior, whether in growth, decline, or stability (Lin et al., 2020).

**Grazing land dynamics**

The investigation results show that the average grassland area over the past five years was 3,013.72 ha. The grass growth rate was found to be 0.45 kg $ha^{-1}$ $day^{-1}$, while the recovery rate was 66.15%, resulting in a total grass regeneration of 1.11 kg $ha^{-1}$ $day^{-1}$. On the other hand, the average relative increase in forage was 1, which was derived by dividing the forage availability by the maximum carrying capacity, as shown in Table 2.

The data indicate that, in addition to grass growth, total grass regeneration reflects the combined effect of natural growth and recovery processes, including regrowth after grazing, fertilization, and favorable climatic conditions. This highlights the potential of managed grazing systems and pasture improvement strategies to increase productivity per hectare (Guáqueta-Solórzano et al., 2025). Carrying capacity refers to the maximum stock level that allows for the sustainable maintenance, or even increase, of forage quality, other vegetation, and related resources (Peters et al., 2016). In short, carrying capacity is defined as the maximum inventory level that a particular land area can sustain sustainably. On the other hand, the relative increase in forage is an indicator used to assess the nutritional quality of forage by combining estimates of digestibility and the potential intake capacity of livestock (Hou et al., 2023).

Table 2 indicates a decline in grassland area and maximum carrying capacity in East Luwu

Table 2. Grassland dynamics in East Luwu Regency

| Years | GA (ha) | CC per are (ind $ha^{-1}$ $year^{-1}$) | TGR (kg $ha^{-1}$ $day^{-1}$) | MCC (ind $ha^{-1}$ $year^{-1}$) | Forage (kg $ha^{-1}$ $day^{-1}$) | RIFQ |
|---|---|---|---|---|---|---|
| 2020 | 3,074.60 | 1.02 | 1.11 | 3,137.20 | 3,138.31 | 1 |
| 2021 | 3,043.85 | 1.02 | 1.11 | 3,105.84 | 3,106.95 | 1 |
| 2022 | 3,013.41 | 1.02 | 1.11 | 3,074.79 | 3,075.90 | 1 |
| 2023 | 2,983.28 | 1.02 | 1.11 | 3,044.06 | 3,045.17 | 1 |
| 2024 | 2,953.45 | 1.02 | 1.11 | 3,013.63 | 3,014.74 | 1 |
| Mean | 3,013.72 | 1.02 | 1.11 | 3,075.10 | 3,076.21 | 1 |

Note: GA = Grassland area, TGR = Total grass regeneration, CC = Carrying capacity, MCC = Maximum carrying capacity, RIFQ = Relative increase in forage quality

Regency over the past five years. The same trend is observed for forage availability, which has also experienced a decrease in quantity. The reduction in grassland area may be caused by the intensity of grazing, which directly impacts the livestock population. Similar elaborations were made by Wang et al. (2016), who showed that increasing grazing intensity significantly reduces vegetation cover and aboveground biomass. Furthermore, Umuhoza et al. (2021) stated that reducing grassland area, maximum carrying capacity, and forage availability can affect livestock population fluctuations.

A recent report by Wang et al. (2024) explained that maximum carrying capacity is crucial for optimizing grasslands to regulate population density. Piipponen et al. (2022) further added that grasslands are the primary source of productivity for livestock, and competition for forage is often limited due to the decreasing availability of land. In addition, Tilahun et al. (2022) and Lei et al. (2023) emphasized that land degradation, including soil compaction and loss of plant biodiversity, contributes to the declining carrying capacity of rangelands, especially under prolonged grazing pressure. This supports the importance of rotational grazing, reseeding native species, and controlling grazing duration as adaptive strategies. The ideal grazing duration was determined to be 3 to 4 months per cycle, allowing sufficient time for pasture recovery and maintaining sustainable forage availability (Gan et al., 2025).

**Livestock population dynamics**

The observations during the study indicate that the mean of the cattle population in East Luwu Regency is 20,411 head. The mean birth rate is 1,393 head, while the mortality rate is 2,635 head. Conversely, the average cattle sales rate is recorded at 806 head, as shown in Table 3. Furthermore, the results of the population growth rate and the feed ratio analysis are presented in Table 4. The analysis shows that the cattle population growth rate was -1,036.5 head per year, indicating an annual decline of this magnitude. Meanwhile, the average feed ratio was 0.03% day, equivalent to 10.93% per year. This condition reflects a scenario in which, over five years, livestock body weight remains unchanged under a constant feed ratio.

Tables 3 and 4 indicate that the cattle growth rate population exhibits a concerning decline. The feed ratio is also alarmingly low; optimal livestock nutrition requires feed intake of 2 to 3% of body weight per day, substantially higher than the observed 0.03% (Keno et al., 2021). The most likely causes of this situation include forage scarcity, extreme drought conditions, and pasture degradation. Azine et al. (2025) revealed that low feed ratios during the dry season severely limit animal productivity, primarily due to forage shortages and degraded pasture quality. Makkar (2018) and Mondal et al. (2025) further suggested that feed competition, climate change, land degradation, and water scarcity constitute significant barriers to sustainable livestock

Table 3. Cattle population in East Luwu Regency over the last five years

| Years | P (ind) | b (ind) | d (ind) | Qs (ind) |
|---|---|---|---|---|
| 2020 | 22,148 | 2,115 | 2,776 | 924 |
| 2021 | 20,464 | 1,700 | 2,128 | 630 |
| 2022 | 20,753 | 1,151 | 2,458 | 924 |
| 2023 | 20,688 | 1,001 | 2,731 | 1,552 |
| 2024 | 18,002 | 1,000 | 3,081 | - |
| Mean | 20,411 | 1,393 | 2,635 | 806 |

Note: P = Current beef cattle population, b = Birth rate, d = Mortality rate, Qs = Sales quantity of cattle

Table 4. The population growth rate of cattle and the mean of the feed ratio

| Years | DN (ind) | Dt (year) | LP (ind year$^{-1}$) | Feed ratio (%) | |
|---|---|---|---|---|---|
| | | | | Day | Year |
| 2020 | 22,148 | 4 | -1,036.5 | 0.03 | 10.93 |
| 2021 | 20,464 | | | 0.03 | 10.93 |
| 2022 | 20,753 | | | 0.03 | 10.93 |
| 2023 | 20,688 | | | 0.03 | 10.93 |
| 2024 | 18,002 | | | 0.03 | 10.93 |
| Mean | 20,411 | 4 | -1,036.5 | 0.03 | 10.93 |

Note: DN = The change in the number of individuals in a population, DN = Population, Dt = Time interval change, LP = Growth rate production systems. Moreover, soil degradation, fluctuations in feed availability, and limited access to nutritional supplements directly contribute to declining cattle productivity and population growth, highlighting the critical role of pasture management in East Luwu. Poorly managed pastures fail to meet the mineral requirements of livestock, as observed in the study area, which is consistent with findings by Duguma and Janssens (2021) and Marchegiani et al. (2025) that inadequate pasture quality leads to reduced livestock performance and increased mortality.

These deficiencies collectively contribute to reduced reproductive performance and increased mortality, thus accelerating the population decline in East Luwu. Similar patterns were reported by Ojo et al. (2024), who identified feed shortages and environmental stress as primary drivers of negative population growth in tropical cattle systems. Therefore, urgent interventions focusing on pasture restoration, drought mitigation, and nutritional supplementation are necessary to reverse this trend and support sustainable cattle population growth in the region.

### Analytical hierarchy process (AHP)

Based on the hierarchical framework established in Figure 4, the AHP method was employed to evaluate the sustainability of beef cattle development in East Luwu. This framework comprised four levels, including the overall goal, criteria, sub-criteria, and five proposed management strategy alternatives. Each alternative corresponded to specific combinations of sub-criteria, reflecting their relevance to sustainability objectives.

The paired comparison matrix of 11 sub-criteria (Table 5) and its normalization (Table 6) yielded a maximum eigenvalue (λ_max) of 12.32. The resulting consistency ratio for the sub-criteria matrix was 0.087 (Table 7), which falls well below the accepted threshold of 0.1, indicating satisfactory consistency and reliability in the judgments. Similarly, consistency ratio values for all five alternatives relative to each sub-criterion also met the acceptable consistency criteria, with values below 0.1 as shown in Table 8. These consistency assessments confirm the robustness and validity of the AHP model in this context.

Following the confirmation of consistency ratio conditions, further analysis determined the main weights of sub-criteria relative to each other (Table 6) and the local weights of each alternative within each sub-criterion (Table 9). Multiplying these weights produced global weights for each alternative (Table 10), which served as the basis for ranking the five management strategies.

The ranking results (Figure 5) revealed that Alternative 4 (IFM-PC) achieved the highest global weight (0.2376), demonstrating its superior effectiveness in addressing sustainability goals. This alternative showed strong associations with key sub-criteria such as forage availability, grazing area, and feed ratio, confirming its holistic and integrative approach to resource management. IFM-PC effectively addresses critical sustainability challenges, including habitat

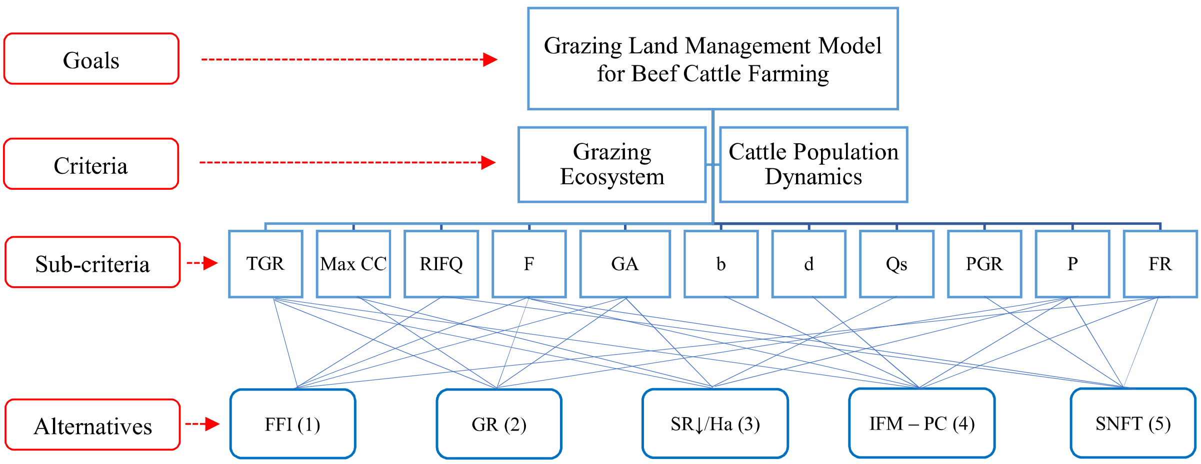


Figure 4. Hierarchical structure of a grazing land management model for beef cattle development in East Luwu Regency

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio, FFI = Feed–Fertilizer intensification, GR = Grazing rotation, SR↓/ha = Reduced stocking rate per hectare, IFM-PC = Integrated feed management and population control, SNFT = Supplementary feeding and new technologies

Table 5. Matrix of sub-criteria pairwise comparison

| Sub-criteria | TGR | MCC | RIFQ | F | GA | b | d | Qs | PGR | P | FR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TGR | 1.00 | 2.00 | 3.00 | 2.00 | 3.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| MCC | 0.50 | 1.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| RIFQ | 0.33 | 0.50 | 1.00 | 2.00 | 2.00 | 3.00 | 3.00 | 3.00 | 2.00 | 3.00 | 2.00 |
| F | 0.50 | 0.50 | 0.50 | 1.00 | 2.00 | 3.00 | 3.00 | 3.00 | 2.00 | 3.00 | 0.50 |
| GA | 0.33 | 0.50 | 0.50 | 0.50 | 1.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.00 |
| b | 0.50 | 0.50 | 0.33 | 0.33 | 0.33 | 1.00 | 2.00 | 3.00 | 2.00 | 2.00 | 2.00 |
| d | 0.50 | 0.50 | 0.33 | 0.33 | 0.33 | 0.50 | 1.00 | 3.00 | 0.33 | 2.00 | 0.33 |
| Qs | 0.50 | 0.50 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 1.00 | 0.33 | 3.00 | 0.50 |
| PGR | 0.50 | 0.50 | 0.50 | 0.50 | 0.33 | 0.50 | 3.00 | 3.00 | 1.00 | 2.00 | 0.50 |
| P | 0.50 | 0.50 | 0.33 | 0.33 | 0.33 | 0.50 | 0.50 | 0.33 | 0.50 | 1.00 | 0.50 |
| FR | 0.50 | 0.50 | 0.50 | 2.00 | 0.50 | 0.50 | 3.00 | 2.00 | 2.00 | 2.00 | 1.00 |
| Sum | 5.66 | 7.50 | 9.32 | 11.32 | 12.15 | 16.33 | 22.83 | 25.33 | 17.16 | 25.00 | 13.33 |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio

Table 6. Normalization of the matrix

| Sub-criteria | TGR | MCC | RIFQ | F | GA | b | d | Qs | PGR | P | FR | weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TGR | 0.18 | 0.27 | 0.32 | 0.18 | 0.25 | 0.12 | 0.09 | 0.08 | 0.12 | 0.08 | 0.15 | 0.17 |
| MCC | 0.09 | 0.13 | 0.21 | 0.18 | 0.16 | 0.12 | 0.09 | 0.08 | 0.12 | 0.08 | 0.15 | 0.13 |
| RIFQ | 0.06 | 0.07 | 0.11 | 0.18 | 0.16 | 0.18 | 0.13 | 0.12 | 0.12 | 0.12 | 0.15 | 0.13 |
| F | 0.09 | 0.07 | 0.05 | 0.09 | 0.16 | 0.18 | 0.13 | 0.12 | 0.12 | 0.12 | 0.04 | 0.11 |
| GA | 0.06 | 0.07 | 0.05 | 0.04 | 0.08 | 0.18 | 0.13 | 0.12 | 0.17 | 0.12 | 0.15 | 0.11 |
| b | 0.09 | 0.07 | 0.04 | 0.03 | 0.03 | 0.06 | 0.09 | 0.12 | 0.12 | 0.08 | 0.15 | 0.08 |
| d | 0.09 | 0.07 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.12 | 0.02 | 0.08 | 0.03 | 0.05 |
| Qs | 0.09 | 0.07 | 0.04 | 0.03 | 0.03 | 0.02 | 0.01 | 0.04 | 0.02 | 0.12 | 0.04 | 0.05 |
| PGR | 0.09 | 0.07 | 0.05 | 0.04 | 0.03 | 0.03 | 0.13 | 0.12 | 0.06 | 0.08 | 0.04 | 0.07 |
| P | 0.09 | 0.07 | 0.04 | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | 0.03 | 0.04 | 0.04 | 0.04 |
| FR | 0.09 | 0.07 | 0.05 | 0.18 | 0.04 | 0.03 | 0.13 | 0.08 | 0.12 | 0.08 | 0.08 | 0.09 |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio

Table 7. Maximum lambda ($\lambda$ max)

| Sub-criteria | weight (w) | A x weight (w) | A x w / w |
|---|---|---|---|
| TGR | 0.17 | 2.07 | 12.17 |
| MCC | 0.13 | 1.62 | 12.46 |
| RIFQ | 0.13 | 1.62 | 12.46 |
| F | 0.11 | 1.35 | 12.27 |
| GA | 0.11 | 1.35 | 12.27 |
| b | 0.08 | 0.96 | 12.00 |
| d | 0.05 | 0.61 | 12.20 |
| Qs | 0.05 | 0.53 | 10.60 |
| PGR | 0.07 | 0.81 | 11.57 |
| P | 0.04 | 0.45 | 11.25 |
| FR | 0.09 | 1.06 | 11.77 |
| $\lambda$ max = 12.32; CI = 0.132; CR = 0.087 | | | |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio, A = Value of each sub-criteria row, CI = Consistency index, CR = Consistency ratio

Table 8. Consistency ratio between alternatives to each sub-criterion

| Sub-criteria | Consistency ratio | Criteria |
|---|---|---|
| TGR | 0.091 | Acceptable (<0.1) |
| MCC | 0.095 | Acceptable (<0.1) |
| RIFQ | 0.050 | Acceptable (<0.1) |
| F | 0.021 | Acceptable (<0.1) |
| GA | 0.055 | Acceptable (<0.1) |
| b | 0.012 | Acceptable (<0.1) |
| d | 0.026 | Acceptable (<0.1) |
| Qs | 0.009 | Acceptable (<0.1) |
| PGR | 0.010 | Acceptable (<0.1) |
| P | -0.071 | Acceptable (<0.1) |
| FR | 0.088 | Acceptable (<0.1) |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio

Table 9. Local weight of alternatives

| Alt. | Local weight | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TGR | MCC | RIFQ | F | GA | b | d | Qs | PGR | P | FR |
| 1 | 0.15 | 0.26 | 0.26 | 0.21 | 0.25 | 0.15 | 0.12 | 0.13 | 0.12 | 0.11 | 0.17 |
| 2 | 0.19 | 0.25 | 0.22 | 0.21 | 0.25 | 0.17 | 0.12 | 0.13 | 0.15 | 0.23 | 0.14 |
| 3 | 0.17 | 0.19 | 0.11 | 0.08 | 0.20 | 0.14 | 0.17 | 0.37 | 0.16 | 0.30 | 0.09 |
| 4 | 0.27 | 0.15 | 0.19 | 0.23 | 0.12 | 0.42 | 0.42 | 0.24 | 0.24 | 0.26 | 0.23 |
| 5 | 0.20 | 0.15 | 0.22 | 0.26 | 0.18 | 0.13 | 0.17 | 0.14 | 0.32 | 0.11 | 0.36 |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio, Alt. = Alternatives

Table 10. Global weight and ranking of alternatives

| Alt. | Global weight of alternative (local weight of alternative x sub-criteria weight) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TGR | MCC | RIFQ | F | GA | b | d | Qs | PGR | P | FR |
| 1 | 0.0255 | 0.0337 | 0.0324 | 0.0227 | 0.0267 | 0.0117 | 0.0064 | 0.0057 | 0.0083 | 0.0041 | 0.0144 |
| 2 | 0.0321 | 0.0321 | 0.0278 | 0.0227 | 0.0267 | 0.0130 | 0.0064 | 0.0057 | 0.0099 | 0.0086 | 0.0120 |
| 3 | 0.0289 | 0.0250 | 0.0139 | 0.0090 | 0.0217 | 0.0109 | 0.0085 | 0.0168 | 0.0110 | 0.0113 | 0.0081 |
| 4 | 0.0455 | 0.0187 | 0.0247 | 0.0243 | 0.0133 | 0.0328 | 0.0216 | 0.0108 | 0.0162 | 0.0097 | 0.0198 |
| 5 | 0.0337 | 0.0187 | 0.0278 | 0.0276 | 0.0192 | 0.0099 | 0.0085 | 0.0063 | 0.0214 | 0.0044 | 0.0310 |

Note: TGR = Total grass regeneration, MCC = Maximum carrying capacity, RIFQ = Relative increase in feed quantity, F = Forage, GA = Grassland area, b = Birth rate, d = Mortality rate, Qs = Sales quantity, PGR = Population growth rate, P = Population, FR = Feed ratio, Alt. = Alternatives

degradation and overexploitation. This approach has been widely adopted in agro-industries, especially aquaculture and fisheries, to mitigate ecosystem damage (Angon et al., 2023), with integrated farming systems and nutrition increasingly recognized as central to sustainable management (Muhie, 2022).

The next highest-ranked strategy was Alternative 5 (SNFT), with a global weight of 0.2085. SNFT emphasizes supplementary feeding and the adoption of innovative technologies to enhance feed quality and production efficiency, supporting long-term sustainability. Its importance is underscored by Gebresenbet et al. (2023), who highlight the need for agricultural systems to improve productivity through optimized feed systems and integrated data management. By contrast, Alternative 1 (FFI) scored 0.1917 and ranked second to last. Despite improving feed and fertilization efficiency, FFI faces sustainability challenges related to environmental impact and high operational costs. Optimizing the manure usage strategy, such as applying appropriate quantities, timing, and distribution methods, can reduce environmental risks and operational expenses while maintaining soil fertility and forage productivity. Moreover, emerging technological solutions that tailor feed

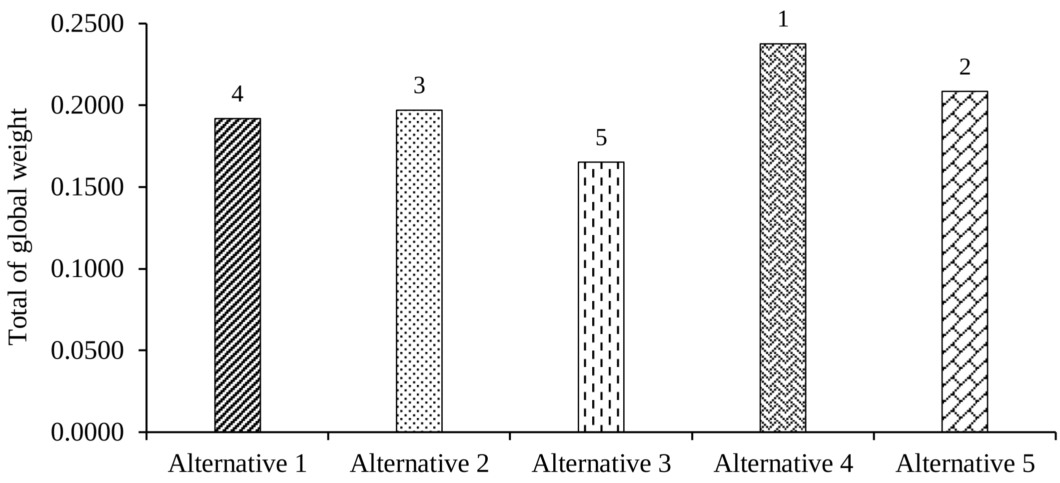


Figure 5. Final ranking of management strategies (alternatives) based on AHP

to individual livestock nutritional needs promise to overcome these limitations (Sonea et al., 2023).

Alternative 2 (growth rate) with a score of 0.1970, suggests rotational grazing contributes to pasture recovery. However, its overall sustainability impact remains lower compared to other strategies. This aligns with Syamsu et al. (2018), who reported low sustainability indices for pasture-based beef cattle systems, highlighting deficiencies across ecological, economic, social, and technological dimensions. While rotational grazing benefits land and feed quality, its implementation complexity and vulnerability to climatic factors may limit effectiveness. Nevertheless, intensive rotational grazing at low stocking densities has positively affected pasture stability and succession dynamics (Russias et al., 2025).

Lastly, Alternative 3 (SR↓/ha) ranked lowest with a score of 0.1652. The ideal stocking rate for grazing lands is generally around 1.4 to 2.1 head per ha for rotational grazing systems (ERS, 2022). Although reducing stocking density can improve pasture conditions, it tends to decrease overall livestock productivity and farmer income if not combined with productivity enhancements. Owensby and Auen (2013) caution that the economic trade-offs of this strategy may reduce the competitiveness of livestock operations unless integrated with improved feed management, rotational grazing, and technological interventions (Baldwin et al., 2022; Ge et al., 2025). In summary, the integration of hierarchical analysis (Figure 4) and the consistent, rigorous evaluation through Tables 5 to 10 supports the prioritization of IFM-PC as the most sustainable and effective management strategy for beef cattle development in East Luwu. While offering specific benefits, the other alternatives exhibit limitations that warrant cautious application or complementary integration within broader management frameworks.

## CONCLUSIONS

Population growth and grazing ecosystem degradation in East Luwu Regency are closely linked, as demonstrated by the system dynamics models (CLD and SFD). Key factors, such as forage availability and population fluctuations, critically affect sustainability. The AHP identified IFM-PC as the optimal management strategy, effectively balancing production efficiency and ecosystem health. IFM-PC's holistic approach mitigates environmental pressures and supports sustainable resource use. These findings provide a validated framework for enhancing long-term productivity and ecological balance in beef cattle development and inform policy decisions on sustainable grazing management. Implementation of IFM-PC is recommended to promote sustainable cattle production and ecosystem conservation in East Luwu. Future research should focus on evaluating the long-term ecological and economic impacts of IFM-PC under varying climate and management scenarios, as well as integrating manure management and rotational grazing practices. Complementary strategies should be integrated to address specific local challenges and improve overall system resilience.

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