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Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:
Marandure, T, Dzama, K, Bennett, J, Makombe, G & Mapiye, C 2020, 'Application of system dynamics modelling in evaluating sustainability of low-input ruminant farming systems in Eastern Cape Province, South Africa', Ecological Modelling, vol. 438, 109294.
https://dx.doi.org/10.1016/j.ecolmodel.2020.109294

DOI 10.1016/j.ecolmodel.2020.109294
ISSN 0304-3800

Publisher: Elsevier

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Application of system dynamics modelling in evaluating sustainability of low-input ruminant farming systems in Eastern Cape Province, South Africa

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Abstract

As a complex and dynamic concept that requires understanding from an ecological, economic and socio-cultural perspective, sustainability of agriculture and food systems is currently being strongly promoted by many governments and rural development practitioners. However, advances in monitoring and evaluating the sustainability of low-input ruminant farming are hindered by a lack of tools that simultaneously consider the interrelationships and dynamic behaviour of the different components of the system. Here we report on the application of a system dynamics model to evaluate the sustainability of low-input ruminant farming systems. This draws on nine indicators grouped as ecological; (soil organic matter, water availability and biomass supply), economic; (livestock productivity, labour supply and household income, and social: (farmer training, credence attributes of ruminant grazing systems and gender equality) to describe system behaviour over a ten-year period. The outputs from model simulations were used to compute index values for each of the indicators and the indices were subsequently used to evaluate sustainability of low-input ruminant farming systems. Household income, gender equality and farmer training had the highest sustainability indices whereas, soil organic matter and biomass supply recorded the lowest values. Overall, the low-input ruminant farming system was found to be moderately sustainable.

Keywords: dynamic feedback mechanisms, complex systems, sustainability evaluation, sustainability index, system dynamics modelling

1 Introduction

Over the past three decades there has been a growing development and policy consensus to promote sustainability in agricultural and food systems, including subsistence-oriented low-input ruminant farming systems (Lush et al., 2014; Vanlauwe et al., 2014; Tedeschi et al., 2015). Ruminants livestock species (i.e. cattle, sheep and goats) in low-input farming systems have similar requirements including shared rangeland resources, dipping, vaccination and marketing facilities (Walters et al., 2016) (Mapiye et al., 2019). As such, decisions made at the community level regarding the use of these common resources, greatly influence management of ruminants at household level and vice-versa (Marandure et al., 2020). It is, therefore, logical that monitoring and evaluation of such systems be conducted simultaneously for all the ruminant species commonly raised within such a low-input farming system. Developing a sustainability evaluation model for such systems requires adequate understanding of the complex, dynamic interactions between the ecological, economic and social dimensions of the system (Singh et al., 2012; Waas et al., 2014; Olde et al., 2016). Considering the complexity involved, a systems thinking approach could help to understand more effectively and holistically low-input ruminant farming systems (Walters et al., 2016).

The sustainability concept exhibits the key characteristics of complex systems which include interconnectedness, interdependence, mutual interaction, dynamic feedback, circular causality and emergent properties (Sterman, 2000; Peano et al., 2015; Allen and Prosperi, 2016). The principles of complex ownership (e.g., juvenile, absentee- and joint/co-ownership), multiple species and roles of ruminant livestock, communal tenure and multi-functionality of rangelands are complex realities that are central to how low-input ruminant farming systems function (Wolfgang and Feldmann, 2003; Tittonell, 2014). Unfortunately, most existing frameworks do not consider these realities when evaluating sustainability of low-input systems and their omission results in inaccurate estimations of their sustainability (Marandure et al., 2018). The current study builds on others that have attempted to provide more nuance to evaluating low-input farming systems (e.g. Molotsi et al., 2017; Shilomboleni, 2017; Marandure et al., 2018) by developing a system dynamics model that holistically considers the complexity of low-input ruminant farming system in sustainability evaluations.

System dynamics is based on the theory of system structures and used to represent complex systems by analysing their dynamic behaviour over time (Sterman, 2000). A system dynamics model is uniquely suited to address the complex interactions and integrate the "soft" and "hard" ecological, economic and social components of low-input ruminant farming into a sustainability evaluation (Walters et al., 2016). Furthermore, it can enhance decision-making through *ex ante* analyses of decision options and through monitoring and evaluation of various interventions (Walters et al., 2016). Application of system dynamics has been reported in demonstrating sustainable development in agriculture (Bastan et al., 2018), alternative production scenarios of mixed crop-livestock systems (Walters et al., 2016), developing management tools for animal production (Tendeshi et al., 2011) and modelling food (Allen and Prosperi, 2016) and bioenergy systems (Musango et al., 2012). To the authors' knowledge, a system dynamics approach has not previously been used to evaluate the sustainability of a low-input ruminant farming system. The current study appreciates that the dynamic interactions between key variables in the low-input ruminant farming system cannot be accurately represented by simple, linear analytical methods adopted for most evaluation tools. The study, therefore, aims to develop and test a system dynamics model for evaluating the sustainability of low-input ruminant farming system in Eastern Cape Province of South Africa.

2 Methodology

2.1 Description of the systems attributes and physical boundaries

Data used in the development of the model was derived mainly from surveys that were conducted in seven rural and peri-urban communities randomly selected from three district municipalities namely; Alfred Nzo, OR Tambo and Chris Hani district municipalities of Eastern Cape Province, South Africa (Figure 1). Community was selected as the unit of analysis in the current study as most agriculture resources such as grazing are defined at this level rather than at household level. Moreover, interventions regarding these resources are more effectively articulated at community level rather than at household level (Marandure et al., 2019).

2.2 Developing sustainability evaluation indicators

As the model is meant to evaluate sustainability of low-input ruminant farming systems, it is essential to identify a set of indicators relevant to the system. This is considered a critical step as the quality of sustainability evaluations is strongly dependent on the pragmatism, representativeness and comprehensiveness of the indicators used in the analysis (Lebacq et al., 2013; Waas et al., 2014; Mascarenhas et al., 2015). The process of consulting farmers becomes pertinent, in this regard, to develop context-specific indicators and related reference values (Chand et al., 2015; Schindler et al., 2015; Moraine et al., 2017). In light of the low education levels and lack of awareness of the sustainability concept by smallholder ruminant farmers in developing countries (Marandure et al., 2019), the limit to development of comprehensive sustainability evaluation indicators by farmers was appreciated.

In the current study, insights from the low-input ruminant livestock farmers' challenges were used as an indirect strategy to develop corresponding pragmatic sustainability evaluation indicators that reflect the context-specific realities of locals. In the interviews, farmers were asked to list the challenges of selected ruminant livestock farming practices that were considered to contribute to sustainability. To broaden the consultation philosophy and improve the comprehensiveness of the process, further challenges were derived from a meta-analysis review of relevant studies conducted in sub-Saharan Africa as described by Marandure (2020). The challenges were then converted into indicators by identifying measurable variables that best represent them (Marandure, 2020). Ultimately, the final set of indicators used in the model comprised of ecological; soil organic, water availability, biomass supply, economic; livestock productivity, labour supply household income, and social; credence value attributes of ruminant grazing systems, farmer training, and gender equality (Table 1).

3 The causal loop diagram

To help develop the preliminary structure of the model, interviews were conducted with 160 low-input ruminant farmers using structured questionnaires to identify key drivers for ruminant management decisions. This process is described explicitly in Marandure et al. (2020) To accomplish the objective of the current study, system dynamics modelling package, VENSIM®, was used to capture data and model the complexities and interactions between the identified indicators. The following provides a synopsis of the key aspects of model development and analysis, including the types of data used to construct a qualitative and quantitative system dynamics model. The general modelling procedure began with the outline of the model and definition of the variables. The relationship between the variables, as presented in the causal loop diagram, was also specified numerically using equations. This was then followed by model simulation and scenarios analyses, and the dynamic behaviour of some key model variables and their differences in different scenarios observed using analysis tools, such as tables and graphs as described by Walters et al. (2016).

A simplified causal-effect relationship between the variables of the models was visualized as the causal loop diagram (CLD) in Figure 2. Feedback loops between variables can be positive or negative. The former is referred to as reinforcing loops and is represented in the CLD by 'R' while, the latter is known as a balancing loop represented by 'B'. The CLD provides a hypothetical representation of how the interviewed farmers implicitly or explicitly indicated how these key system components interact to form a system structure (Figure 2). The hypothetical analysis of system structure through the CLD helps to characterize feedback loop polarity, which can be used to support subsequent simulation outputs and findings. The CLD was then used to inform the structure of the model, where components were basically parameterized and simulated using qualitative and quantitative data from the interviews with low-input ruminant farmers in South Africa and meta-analysis of published literature on challenges in low-input ruminant systems in sub-Saharan Africa. Although, as a weakness of the model, it can be argued that such a broad meta-analysis potentially obscures the context-specific aspects of the study, it was assumed that and confirmed by Marandure (2020) that low-input farmers in sub-Saharan Africa have related challenges. The challenges derived at local level were therefore, used to reinforce secondary data from the meta-analysis. A time horizon of 10 years from 2018 to 2028 was used to take into account the short and medium-term effects on the selected sustainability indicators. The time horizon was informed by the fact that most intervention strategies in low-input farming systems are short to medium term covering a time period of between 5-10 years (Shilomboleni, 2017).

4 The model

The model comprised 11 sub-models including, the soil fertility, biomass supply, water supply, cattle, goats, sheep, labour supply, household income, farmer training, the credence value attributes of grazing ruminant systems and gender equality sub-models. The subsequent sections are dedicated to describing the individual sub-models. As stock and flow diagrams are inherently quantitative, it was necessary to numerically define each of the model parameters, through formulas, direct numerical values, or normalized graphical functions. Values for each parameter in the model were derived from primary data from interviews or estimated from secondary data.

4.1 Ecological sub-models

Initial conditions for the ecological sub-model are shown in Table 2. Soil organic matter was considered an important indicator of soil fertility (Rosa and Sobral, 2008). It was modelled as a single stock sub-model enhanced by decomposition of humus. It is diminished by plant uptake as well as by natural volatilisation as shown in the following equation:

Soil organic matter = INTEG [(Soil organic matter addition - Soil organic matter sink) / Initial soil organic matter].

Biomass supply was modelled as biomass flow through the system per annum represented as follows:

Biomass supply (kg) = INTEG [(Rangeland biomass production - Rangeland biomass depletion)/ Initial rangeland biomass]The stock of biomass at any given time was a factor of rangeland biomass production which is influenced by seasonal factors especially, temperature and rainfall, and edaphic factors, particularly, soil fertility represented in the model as soil organic matter content. It was given as:

rangeland biomass production (kg/year) = Effect of season on rangeland biomass × Effect of soil organic matter on rangeland biomass production × Rate of rangeland biomass production × Biomass supply.

Rangeland biomass was harvested during foraging based on biomass density and the desired nutrient requirements of cattle, goats and sheep. Desired animal nutrient requirements were calculated as proportions of animal live body weight using the Total Digestible Nutrients (TDN) technique. The TDN is defined as the sum of available TDN from dedicated grazing and/or browsing on the rangeland and from access to crop residues after harvest (Walters et al., 2016). This is represented in the following equation:

Rangeland biomass depletion (kg/year) = Desired consumption × Effect of density on foraging.

Total digestible nutrients requirements for the different animal species was parameterised according to the age categories of animals represented by different stocks. Drinking water supply in the current model was taken to represent surpluses after meeting the demand for water. It was modelled as a single stock sub-model which was replenished by surface water inflow and depleted by surface water outflow, ruminant water consumption and loss through evapotranspiration as follows:

Water supply (m^3) = INTEG [(Surface water inflow - Surface water withdrawal)/Initial surface water].

Sub-surface flow of water to the surface and water infiltration into ground water sources as other factors that increase or reduce stock were however, not considered in this model due to lack of data.

4.2 Economic sub-models

Initial conditions for cattle, goats and sheep productivity sub-models are represented in Table 3, 4 and 5, respectively. The species-specific sub-models (cattle, sheep and goats) were modelled as a three stock sub-model comprising of neonates/newborn, weaners and mature animals as represented in the following relationships:

Ruminant neonates= INTEG [(births - weaning - preweaning mortality)/ 980)]

Ruminant weaners/withers = INTEG [(weaning - postweaning mortality - retention)/ 686)]

Mature ruminant = INTEG [(purchases + received as gifts + retention) – culling)/ Initial herd or flock sizes]

Herd/flock sizes were determined over time by the influence of weaning rate per adult female and limited by available feed and water. Increases in herd/flock size were calculated as the number of adult females in the herd/flock multiplied by the weaning rate per adult female plus other additions through purchases and/or gifts received. Exits from the system were assumed to comprise natural deaths and slaughter, as well as donations to others or sales.

The labour supply sub-model was explored to assess labour availability for ruminant farming. It is a single stock sub-model comprising labour supply measured in person as follows:

Labour supply = INTEG [(Increasing labour - Decreasing labour)/ Initial labour supply]

Labour supply is increased either by family births or hired labour and lowered by off-farm employment which is linked to net migration especially by youths. The labour supply is thus, linked to the population sub-model of the communities under the current study. Household income was modelled as the annual dynamic variability in wealth, largely from crops and livestock sales as follows:

Household income (Rands) = INTEG [(Crop to income + Ruminants to income - Investments)/ 2000].

Additional wealth generated from off-farm wages/salaries, social grants or pensions were not incorporated in the model, as that is not directly linked to ruminant production. Income from ruminants was considered on both flow and final products. Flow products were defined as intermediate products such as, milk, manure and draft power, while, end products as sale or slaughter of the animals.

4.3 Social sub-models

Famer training is critical to improve the intrinsic human capital within local ruminant farmers (Marandure et al., 2019). Interactions between farmers during training also present opportunities for developing functional social networks and fostering knowledge transfer and peer-to-peer learning among low-input ruminant farmers (Segnon et al., 2015; Marandure et al., 2019). The farmer training sub-model consisted of one stock which was influenced by new farmers' recruitments and depleted by newly trained farmers as represented in the following equation:

Farmers in training = INTEG [(Recruiting farmers for training - New trainees)/ Initial trained farmers].

Credence attributes of ruminant grazing system are often omitted from evaluations resulting in underestimation of system sustainability. Factors that enhance credence attributes of ruminant grazing system include the effect of healthfulness of food, food safety and animal welfare. Declining or degraded rangelands diminish perceptions of credence attributes. The relationship of credence value attributes is represented by the following equation:

Credence value attributes of grazing systems = INTEG [(Increasing credence value attributes - Decreasing credence value attributes)/ Initial credence value attributes].

Promoting the involvement of women in ruminant farming helps to elevate their status in society (Kristjanson et al., 2010). The gender equality sub-model consisted of one stock with the inflow comprising new women recruited in ruminant farming and the outflow being women abandoning ruminant farming as represented in the following equation:

Women farmers = INTEG [(Increasing women farmers - Decreasing women farmers)/ Total women farmers].

5 Model validation

Model validation is an essential iterative process to understand the limitations and robustness of the developed model (Marcis et al., 2019). It is a continuous process of testing and building confidence in the model keeping note of the environment in which the model is designed to operate and the questions it aims to answer (Rasch et al., 2016). The validation process is based on a different number of tests including structural and behavioural validity as well as expert opinion, as no formalized methodologies and validation tools exist in systems dynamics modelling (Tanure et al., 2015). The different tests will be described in detail in subsequent sections. In this regard, a model can be classified as good quality or poor quality suitable or not suitable but not correct or incorrect (Walter et al., 2016).

5.1 Structural validity

Validity of the internal structure of the model is fundamental to determine how well the structure of the model matches that of the real world. As descriptions of system structure are generally not available, they have to be extracted from the mental models of people familiar with the system (von Loeper et al., 2016). In this study, the structural validation process began at the initial stage of model building when the interrelationships between identified model parameters were conceptualised.

5.2 Behavioral validity

This test determines the consistency with which model outputs match real world behaviour. In case of data availability, this can ideally be achieved through use of available time-series data otherwise correlations of mental models with established reference models are used (Musango et al., 2012). In the current study, behavioural validity was achieved through sensitivity analysis where the model's sensitivity to various assumptions including, changes in water availability and ruminant numbers were tested using the Monte-Carlo sensitivity simulation platform of the Vensim® software.

5.3 Expert opinion

Qualitative validation using expert opinion was also used in this study to assess the model usefulness, importance and quality. During development and testing of the model, a total of five system dynamics specialists from the systems dynamics South African chapter were consulted based on their accessibility by the researcher and willingness to participate. Principles of the Delphi technique were followed to benefit from the collective intelligence of specialist individuals in system dynamics modelling on a collective basis. Consultations were conducted over two phases. The first phase involved the structural components of the model and the second phase of targeted the functionality of the model and scientific relevance of model results. In addition, the second phase aimed to develop consensus from participating experts on model structure and function.

6 Computing sustainability indices

Sustainability evaluation was achieved by running simulations and analysing the baseline or reference mode outputs of all the identified indicators. The differences between initial (2018) and final (2028) values, from the reference mode outputs of simulations, for each indicator were used to develop a ranking system as per Walters et al., (2016), where the larger the difference the higher the rank. The proportion of the rankings were then used to calculate sustainability indices (Walters et al., 2016). Sustainability indices were then presented in the form of a radial or AMOEBA diagram. The index values were not integrated to give a single composite measure of sustainability to avoid indicators with higher indices values compensating for those with lower values. Sustainability of each indicator was determined using a classification described by Atanga et al. (2013) where, unsustainable indicators had values between 0 and 0.33, moderately sustainable; 0.34-0.66 and sustainable; >0.66. A system was then considered to be sustainable when 66% of the selected indicators had sustainable index values. Likewise, when 66% of the indicators have unsustainable index values, then the system is considered to be unsustainable. Any values between the two extremes represent a moderately sustainable system.

7 Results

7.1 Model simulation and analysis

Analysis of the stock flow model involved running model simulations and evaluating the quantitative yearly averaged outputs of the selected indicators developed to determine sustainability of the low-input ruminant farming system in the Eastern Cape Province, South Africa over a production time horizon of ten years.

7.1.1 Ecological indicators

The baseline simulation runs of the model for ecological indicators are presented in Figure 3. Maximum soil organic matter content of 5000kg was recorded and thereafter it started to decline gradually (Figure 3a). With the model set to run from the year 2018 to 2028, water supply in the studied communities was modelled as water surplus as a result of supply and demand for water. It was projected that there would be a balance between water consumption and water supply throughout the period under review. Biomass supply showed a similar trend to soil organic matter content having recorded a maximum production capacity of 36 million kilograms of biomass per year in 2018 and thereafter start to decrease gradually (Figure 3b).

7.1.2 Economic indicators

For ruminants' productivity, only stock dynamics of mature animals were considered in the current study. Cattle (Figure 4a) and goats (Figure 4b) sub-models recorded similar trends while, that of sheep (Figure 4c) was slightly different. Mature cattle numbers increased from an initial value of 950 recorded in 2018 to peak at maximum of 1200 between the year 2020 and 2022. Thereafter, mature cattle numbers gradually declined to 1000 animals recorded in 2028. Similarly, goat numbers initially increased from 2000 to a maximum of 2500 recorded between 2020 and 2021 before starting a gradual decline to a value of 1900 recorded in 2028. Mature sheep numbers decreased gradually from a maximum of 3200 to a minimum of 1500 recorded in 2018 and 2028, respectively. As presented in Figure 5, labour supply projected a gradual decline over the years from a maximum of 600 people per year in 2018 to a minimum of 250 people in 2028. Minimum household income was recorded as R2000/year in 2018, it then increased and was projected to peak at R14000/year between 2020 and 2022. Thereafter it decreased slightly over the years to a projected value of R12500/year in 2028.

7.1.3 Social indicators

Farmers in trainings were recorded to increase from a minimum of 590 farmers/year in 2018 to a maximum of 700 farmers/year in 2028 (Figure 6a). Due to a lack of historical and current data on benefits accrued through credence attributes of ruminant grazing systems, perceptions of farmers, from the empirical work undertaken in Eastern Cape Province, on this issue were used for evaluation. Perceptions were evaluated using a perception index scale (Tatlidil et al., 2009) ranging from -1 (strongly negative perception) to +1 (strongly positive perception).

Perception values were recorded as constant at +0.3 throughout the study period (Figure 6b). The number of women involved in farming was recorded to peak at an average of 3000/year in 2028 having increased exponentially from a minimum of 500 in 2018 (Figure 6c).

7.2 Sustainability evaluation

Table 6 shows the values used to rank the indices computed in the current study and the subsequent computation of sustainability indices. The indices were then presented in Figure 7 in the form of a radial diagram. Assessment of the indices from model output show that household income and gender equality had higher sustainability indices. Soil fertility and biomass supply had the lowest sustainability indices. Twenty-seven percent of the indicators were in the sustainable and unsustainable categories while, the rest were moderately sustainable. Overall the low-input ruminant farming system in Eastern Cape Province, South Africa was categorised as moderately sustainable.

8 Discussion

The observation of declining trends of average values for soil organic matter and biomass supply is consistent with previous studies that partly attributed declining rangeland resources due to poor soil fertility and overharvesting (Ayantunde et al., 2011; Ford Denison and McGuire, 2015). In general, growing livestock populations, rangeland conversions and a decline in traditional authority constantly put pressure on open access livestock feed resources leading to excessive depletion of soil nutrients and over consumption of biomass (Moyo et al., 2008; Bennett et al., 2013). The observed livestock trends which followed similar patterns as soil organic matter and biomass supply partly support this notion. According to Rasch et al. (2016) the common perception among experts and policymakers is that communal rangelands are overstocked. The perception influences the government and rural development agencies to consistently follow a policy of destocking both to reduce pressure on the available rangeland and improve livestock production in the communal areas (Moyo et al., 2008).

Except for sheep that recorded substantial decline in numbers over the years in the current study, cattle and goat numbers are consistent with records demonstrating that the communal livestock numbers have fluctuated around a stable average over the past century, albeit at low productivity (Scholtz et al., 2008). Various scholars advocated for effective management, but this is complicated by the communal ownership of rangelands, which makes coordinated decision-making difficult (Moyo et al., 2008). Ultimately, the low sustainability indices observed for biomass supply and soil organic matter partly support literature that report the two among other ecological indicators that diminish sustainability in low-input farming systems (Waas et al., 2014; Bertocchi et al., 2016; Srinivasa Rao et al., 2018). The water supply trend and indices may have presented a misleading picture of adequate water resources in the areas under the current study. True to the projection of the model, water adequacy for livestock farming in the areas may not be a misconception in the studied areas as over 80% of households were reported to have piped water to their homesteads (Webster and Ras, 2016).

The observed gradual decline in labour supply recorded in the current study is consistent with various studies that recorded lack of adequate manpower and others that predicted further loss of potential manpower mainly through rural to urban migration (Marta-Costa and Costa, 2011; Tittonell and Giller, 2013; Senyolo et al., 2018). FAO (2009) predicted that over 80% of the rural population in developing countries will migrate to urban areas by the year 2050. While, this raise concerns over how the growing urban population will be accommodated and fed, there are further anxieties over the substantial gap in labour left by migrating individuals in rural areas. In terms of sustainability evaluation, the moderate index value for labour supply was considered to drive relatively modest level of sustainability.

High livestock income recorded in the current study is in contrast with several studies that reported low values (Waithaka et al., 2006; Kocho et al., 2011). The discrepancies may be emanating from the fact that unlike in most studies where income was only considered from sale of live single-species animals, the current study evaluated potential income from all products and services of ruminants in the low-input ruminant farming system. The idea of considering income from multiple ruminant species is logical as it increases stability. For example, cattle may represent a long-term investment whereas goats and sheep are primarily shorter-term investments with relatively lower value. The inclusion of income from flow animal products such as, milk, manure and draft power is necessary as it represent reality of low-input ruminant farming (Thamaga-Chitja and Morojele, 2014).

Income from flow products is part of the reason why some low-input ruminant farmers argue that their production effectively meets their local expectations and does not require reform while, experts consider them as economically wasteful and destructive of natural resources (Dougill et al., 2010; Faku and Hebinck, 2013). Such claims by low-input farmers is supported by studies from de Ridder and Wagenaar (1986) that compared smallholder mixed farming with ranching and found that after considering flow products, smallholder cattle keeping was more productive, not only per hectare but also per cow. It is, however, appreciated that household economy of low-input ruminant farmers is often multisectoral and the farm income is supplemented by income from handicrafts, trade, wage labour, remittances or pensions (Harrison et al., 2001). Family members and extended family members are also obligated to help relatives and neighbours in need and can expect the same in return (Jakoby et al., 2015).

However, these non-farming income sources were not considered in the model as it is out of scope of the study. Otherwise the relatively high index value of household income reflects its importance as one of the major drivers contributing towards greater sustainability in low-input farming.

The observation of gradual increases in farmer training and women involvement in ruminant farming may reflect enhanced development focus on both aspects by several governments and development agencies in developing countries. Both indicators present opportunities to spread awareness of the sustainability concept and promote sustainable ruminant production practices. According to DeWaal, (2014) incorporating the sustainability concept in farmer training programs helps them to understand the wider spectrum of their challenges and capacitate them to formulate their own solutions within the confines of the available human and material resources. Involving more women in ruminant farming helps to elevate their social status and disregards the common perception that livestock development programs favour the wealthier sectors of society rather than the most vulnerable groups such as women and youth (Sseguya et al., 2018). Shah et al. (2013) mentioned that elevated social status of women translates to access or even authority over a broader base of community resources which gives them the necessary leverage to lobby for support from government and other organizations in parallel with their male counterparts. Ironically, both farmer training and gender equality indicators have comparable and moderate indices reflecting relatively modest contribution towards sustainability.

The constant and slightly positive perceptions of farmers on credence attributes of grazing ruminant systems may be within expectations as issues of food safety and healthfulness of products as well as animal welfare are considered to be elitist and reserved for wealthy (Thanh et al., 2015). This notion is supported by studies that suggest that consumers are increasingly becoming conscious of animal welfare, food safety and healthfulness of food products and are therefore, demanding products from production systems that uphold such standards (Umberger et al., 2009). Low-input consumers in developing countries might not be concerned about credence attributes but it is expected that these issues will become more important in future (Umberger et al., 2009). The index value for credence attributes of grazing ruminants suggest moderate contribution towards sustainability of the low-input ruminant system.

It should be appreciated that computer simulations have their limitations as they only provide a simple representation of the reality that is being investigated. It is practically impossible to capture all the inherent realities of the low-input farming system. However, the model simulations provided enough information to allow authors to reach conclusions that are relatively intuitive in the context of low-ruminant ruminant farming in the Eastern Cape Province, South Africa. Future research efforts could improve model utility and applicability by calibrating model parameters and provide links to improve understanding of the important drivers influencing ruminant farming. Participation in the modelling process by stakeholders improves intimate understanding of the system and enhances decision making by promoting creation of more adaptable and responsive management practices and production strategies for improved sustainable farming systems. In future, group model building exercises with all stakeholders will help to minimise subjectivity of the models.

9 Conclusion

The current study demonstrated the application of the sustainability evaluation of low-input ruminant farming model to explore the dynamic interactions of ecological, economic and social drivers of the system. The sustainability evaluation system showed that the low-input ruminant farming system in Eastern Cape Province, South Africa was moderately sustainable. The sustainability of the low-input ruminant farming system was mainly enhanced by water supply, household income, and gender equality and diminished by soil organic matter content and biomass supply. It is recommended to holistically consider rectifying factors diminishing sustainability while taking cognisance of interactions between factors.

Acknowledgements

The authors would like to acknowledge the contribution of ruminant farmers from Matatiele, Ndakeni and Butterworth through their time and information which provided the bulk of data used in the current study.

Funding

The funding contribution of the Department of Science and Technology-National Research Foundation (DST-NRF) Centre of Excellence (CoE) in Food Security (grant number: 140102) is hereby acknowledged.

Conflict of interest

Authors declare that there is no conflict of interest.

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Table 1: Sustainability indicators used to evaluate sustainability of low-input ruminant farming systems in Eastern Cape Province, South Africa

Sustainability dimension	**Indicator**	**Description**	**Units**
Ecological	Soil organic matter content	Measures the amount of soil organic matter	Kg/ha
	Biomass supply	Measures biomass abundance	kgDM/ha/Year
	Water supply	Measures drinking water availability for livestock	Ltr/Year
Economic	Livestock productivity	Measures increases or decreases in ruminant number	Cow or Goat or Sheep
	Household income	Measures the proportion of household income that is contributed by livestock	Rand/Year
	Labour supply	Measures manpower availability	Person/Year
Social	Credence attributes of grazing systems	Measures the hidden benefits of ruminant grazing systems	Dimensionless
	Farmer training	Measures capacity building potential of communities	Person/Year
	Gender equality	Measures the involvement of women in ruminant farming	Person

Table 2: Biomass supply sub-model stock flow model parameter summary

Parameter	Value	Unit	Meaning	Source
Initial rangeland biomass	216 000	Kg	Assuming a portion of forage production that is available for grazing 720ha rangeland and 300 kgDM/ha of biomass/year.	Farmer survey (Victoria and Gippsland, 1995)
Maximum rangeland biomass	360 000	Kg	Assuming a 720ha rangeland and 500 kgDM/ha of biomass/year	(Victoria and Gippsland, 1995)
Rangeland biomass production rate	0.02	Dimensionless	Assuming production rate of 20 kgDM/ha	(Victoria and Gippsland, 1995)
Surface water resources	540	mm/Year	Assuming that 90% of mean annual rainfall (600mm/year) recharges surface water resources	(Webster and Ras, 2016)

Table 3: Cattle sub-model stock flow model parameter summary

Parameter	**Value**	**Unit**	**Description**	**Source**
Initial cattle herd size	1440	Cow	Size of cattle herd at the start of model	Farmer interviews
Cattle neonates	288	Cow	Proportion of newly born calves	(Nowers et al., 2013) (Barrett, 1991)
Cattle weaners	201	Cow	Proportion of weaned cattle	(Nowers et al., 2013) (Barrett, 1991)
Cattle female proportion	0.6	Cow	Proportion of reproductive mature females	(Nowers et al., 2013) (Barrett, 1991)
Cattle calving rate	0.5	Dimensionless	Proportion of mature cows producing calves per year	(Nowers et al., 2013) (Barrett, 1991)
Cattle weaning rate	0.7	Dimensionless	Rate at which calves are weaned	(Nowers et al., 2013) (Barrett, 1991)
Cattle proportion of calves	0.2	Dimensionless	Proportion of calves to the total herd	(Nowers et al., 2013) (Barrett, 1991)
Weaning age	1	Year	Average age at which nursing calves are weaned	(Nowers et al., 2013) (Barrett, 1991)
Age at first calving	4	Year	Average age at which heifers drop their first calves	(Nowers et al., 2013) (Barrett, 1991)
Cow longevity	8	Year	Average time that an animal stays on the farm	(Nowers et al., 2013) (Barrett, 1991)
Cattle commercial offtake rates	0.02	Dimensionless %	Rate of selling cattle	(Nowers et al., 2013) (Barrett, 1991)
Cattle slaughter offtake rates	0.03	Dimensionless%	Rate of cattle slaughter on farm for various purposes	(Nowers et al., 2013) (Barrett, 1991)
Mature cattle dry matter intake	5400	Kg/Cow/Year	Assuming dry matter intake of 5% of mature body weight of 450kg	(Victoria and Gippsland, 1995)
Cattle weaners dry matter consumption	2700	Kg/Cow/Year	Assuming dry matter intake of 5% of mature body weight of 180kg	(Victoria and Gippsland, 1995)
Cattle neonates dry matter consumption	300	Kg/Cow/Year	Arbitrary value	
Mature cattle water demand	21600	L/Cow/Year	Assuming water requirement of 4L/kg DM	(Meissner et al., 2013)
Cattle weaners water demand	10800	L/Cow/Year	Assuming water requirement of 4L/kg DM	(Meissner et al., 2013)
Cattle neonates water demands	1200	L/Cow/Year	Assuming water requirement of 4L/kg DM	(Meissner et al., 2013)

Table 4: Goat sub-model stock flow model parameter summary

Parameter	**Value**	**Unit**	**Description**	**Source**
Initial goat population	2040	Goat	Size of goat flock at the start of model	Farmer interviews
Goat neonates	980	Goat	Number of newly born kids	(Coetzee, 1998)
Goat withers	686	Goat	Number of weaned goats	(Coetzee, 1998)
Goat female proportion	0.6	Goat	Proportion of reproductive mature females	(Victoria and Gippsland, 1995)
Goat kidding rate	0.8	Dimensionless	Rate of production of new kids	(Victoria and Gippsland, 1995)
Goat weaning rate	0.7	Dimensionless	Rate of weaning nursing kids	(Coetzee, 1998)
Goat proportion of calves		Dimensionless	Number of kids as a proportion of the flock	(Coetzee, 1998)
Pre-weaning kid mortality	0.3	Dimensionless	Proportion of kids that die before weaning	(Coetzee, 1998)
Goat natural mortality rate	0.07	Dimensionless	Proportion of goat deaths due to natural causes	(Coetzee, 1998)
Weaning age	0.6	Year	Average age at which nursing kids are weaned	(Coetzee, 1998)
Age at first kidding	1	Year	Average age at which a nanny drops its first kid	(Victoria and Gippsland, 1995)
Goat longevity	5	Year	Average time a goat stays on the farm	(Victoria and Gippsland, 1995)
Goat commercial offtake rates	0.06	Dimensionless	Rate of selling goats	(Victoria and Gippsland, 1995)
Goat slaughter offtake rates	0.02	Dimensionless	Rate of goat slaughter for various reasons	(Victoria and Gippsland, 1995)
Mature goat dry matter intake	3600	Kg/Goat/Year	Assuming dry matter intake of 3% of mature body weight being 30kg	(Victoria and Gippsland, 1995)
Goat weaners dry matter consumption	1800	Kg/Goat/Year	Assuming dry matter intake of 3% of mature body weight being 15kg	(Victoria and Gippsland, 1995)
Goat neonates dry matter consumption	150	Kg/Goat/Year	Arbitrary value	
Mature goat water consumption	7200	L/Goat/Year	Assuming water requirement of 2L/kg DM	(Victoria and Gippsland, 1995)
Goat withers water consumption	3600	L/Goat/Year	Assuming water requirement of 2L/kg DM	(Victoria and Gippsland, 1995)
Goat neonates water consumption	300	L/Goat/Year	Assuming water requirement of 2L/kg DM	(Victoria and Gippsland, 1995)

Table 5: Sheep sub-model stock flow model parameter summary

Parameter	Value	Unit	Description	Source
Initial sheep population	3240	Sheep	Size of sheep flock at the start of model	Farmer interviews
Sheep neonates	1555	Sheep	Number of newly born lambs	(Victoria and Gippsland, 1995)
Sheep withers	1.088	Sheep	Number of weaned sheep	(Victoria and Gippsland, 1995)
Sheep female proportion	0.6	Dimensionless	Proportion of reproductive mature females	(Victoria and Gippsland, 1995)
Sheep lambing rate	0.8	Dimensionless	Rate of production of new lambs	(Victoria and Gippsland, 1995)
Sheep weaning rate	0.7	Dimensionless	Rate of weaning nursing lambs	(Victoria and Gippsland, 1995)
Sheep proportion of calves		Dimensionless	Proportion of lambs as a proportion of the flock	(Victoria and Gippsland, 1995)
Sheep natural mortality rate	0.3	Dimensionless	Proportion of sheep that die of natural causes	(Victoria and Gippsland, 1995)
Weaning age	0.07	Year	Average age at which nursing lambs are weaned	(Victoria and Gippsland, 1995)
Age at first lambing		Year	Average age at which an ewe lamb drops its first kid	(Victoria and Gippsland, 1995)
Sheep longevity	4	Year	Average time a sheep stays on the farm	(Victoria and Gippsland, 1995)
Sheep commercial offtake rates	0.06	Dimensionless	Rate of selling sheep	(Victoria and Gippsland, 1995)
Sheep slaughter offtake rates	0.02	Dimensionless	Rate of goat slaughter for various reasons	(Victoria and Gippsland, 1995)
Mature sheep dry matter intake	3600	Kg/Sheep/Year	Assuming DMI of 3% of mature body weight being 15kg	(Victoria and Gippsland, 1995)
Sheep weaners dry matter consumption	1800	Kg/Sheep/Year	Assuming DMIof 3% of mature body weight being 30kg	(Victoria and Gippsland, 1995)
Sheep neonates dry matter consumption	150	Kg/Sheep/Year	Arbitrary value	

Table 6: Sustainability index ranking for indicators used to evaluate sustainability of the low-input ruminant farming system in Eastern Cape Province, South Africa

Indicator	**Initial value**	**Final value**	**Difference**	**Direction sign**	**Ranking**	**Index**
Mature cattle	950	1000	50	↑	8	0.73
Mature goats	2200	1900	300	↓	5	0.45
Mature sheep	3300	1500	1 800	↓	3	0.27
Biomass supply	30000000	2000000	28000000	↓	1	0.09
Water supply	0	0	0	-	7	0.64
Soil organic matter	5000	1500	3500	↓	2	0.18
Labour supply	600	250	350	↓	4	0.36
Household income	2000	12500	10500	↑	11	0.91
Farmer training	500	700	200	↑	9	0.82
Credence attributes	0.3	0.3	0		6	0.55
Women in farming	500	3000	2500	↑	10	0.91

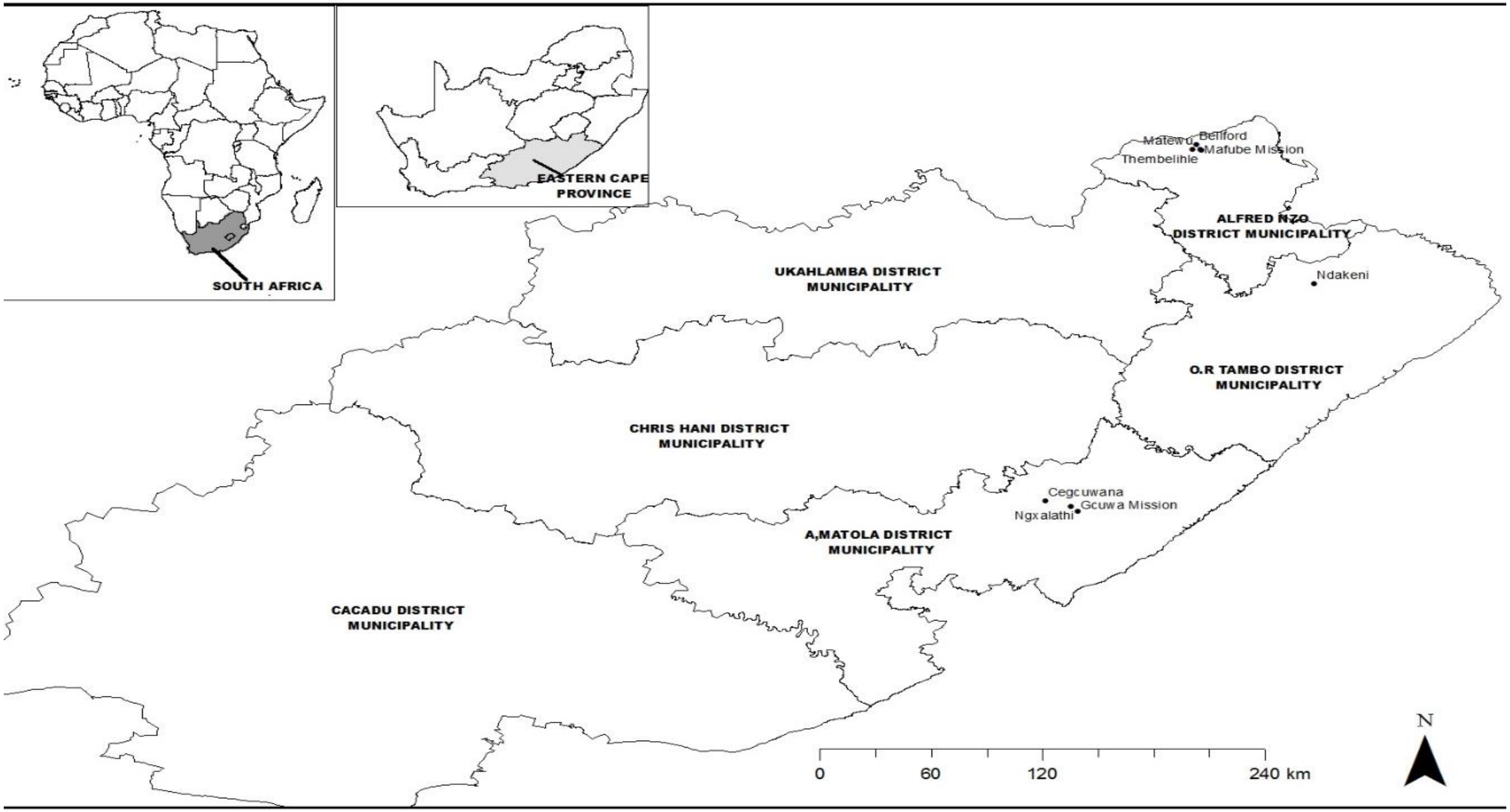


Figure 1: Map showing the surveyed areas in the Eastern Cape Province of south Africa

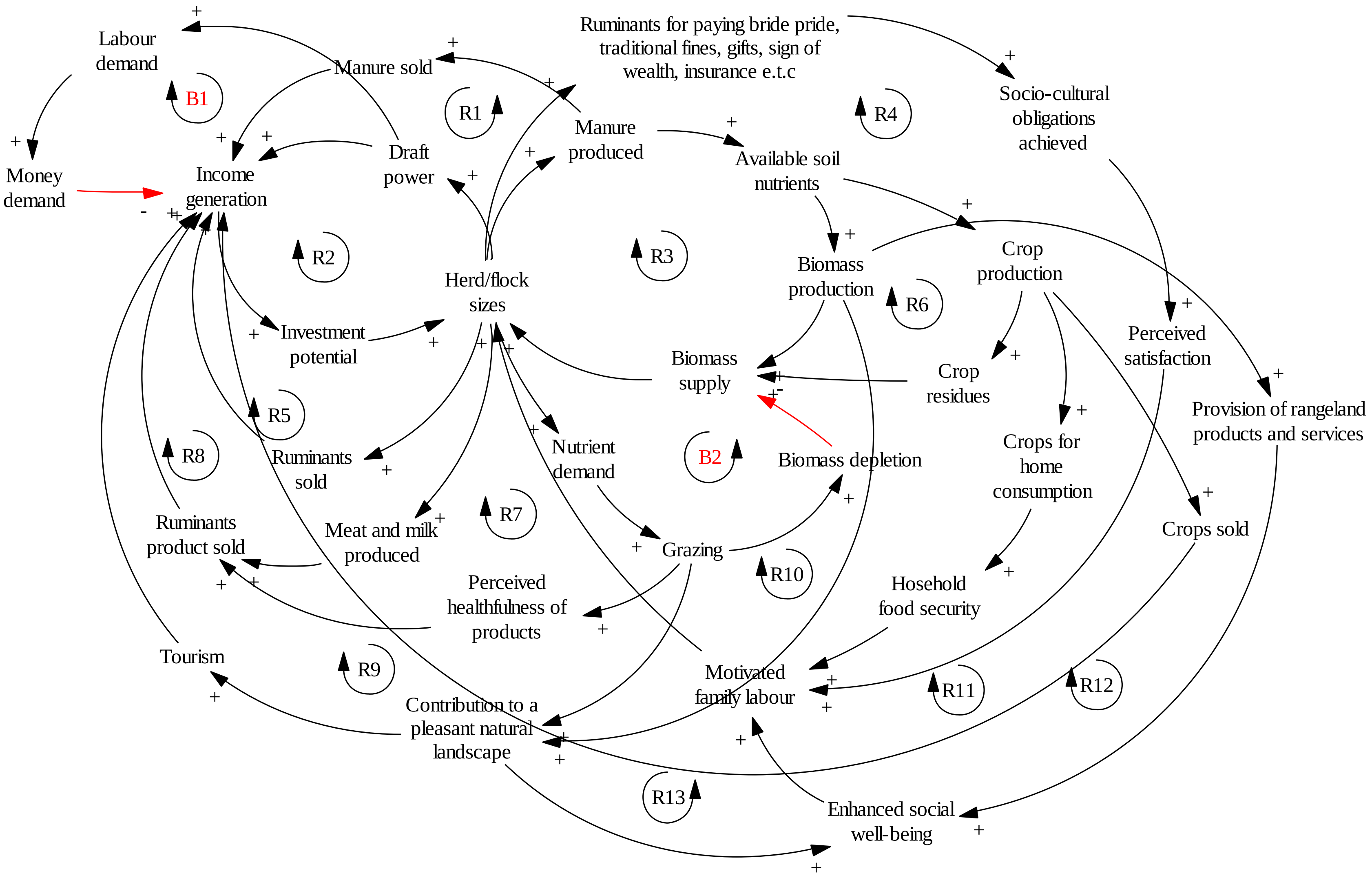
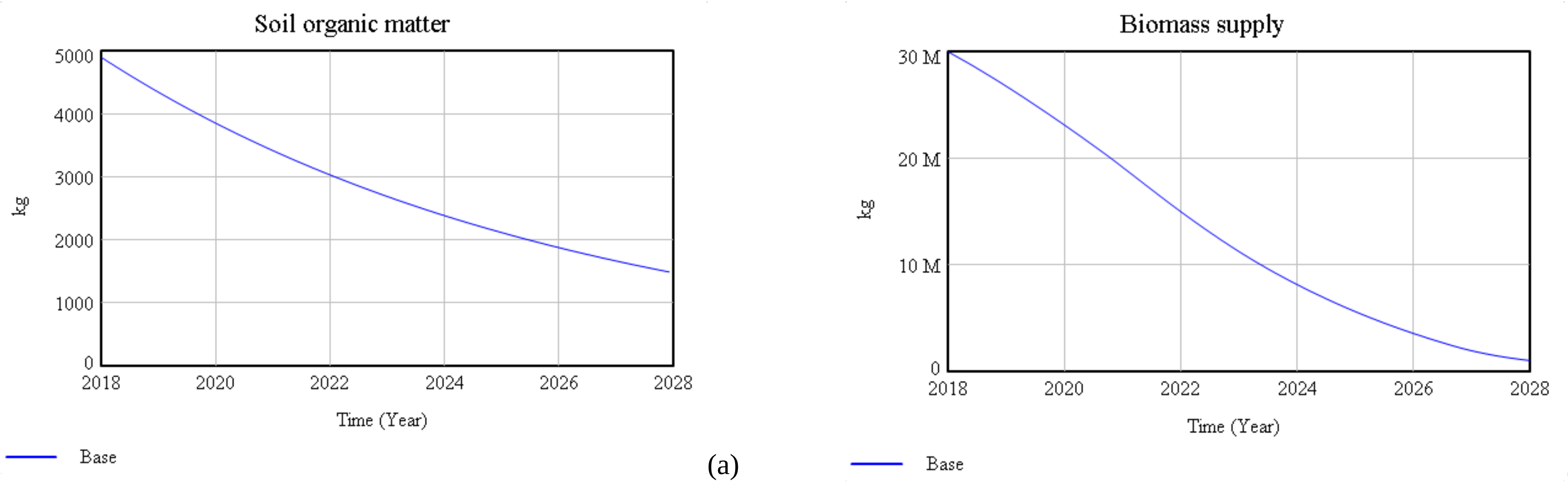


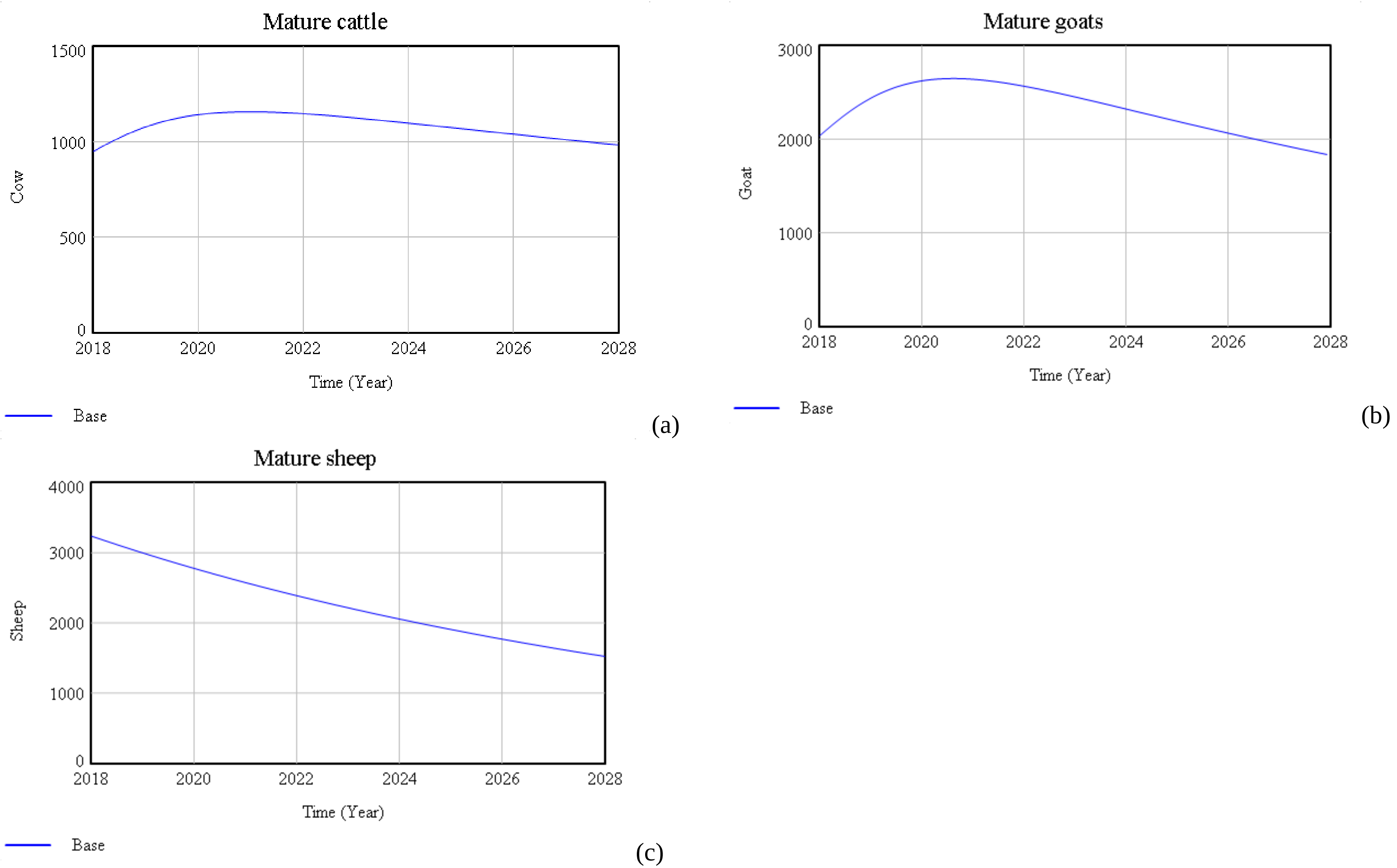
Figure 2: Causal loop diagram of key drivers of smallholder ruminant farming systems as conceptualised by farmers in Eastern Cape Province, South Africa



(a)

(b)

Figure 3: Reference base modes for the soil organic matter (a) and biomass supply (b) sub-models used to evaluate sustainability of the low-input ruminant farming system in Eastern Cape Province, South Africa



(a)

(b)

(c)

Figure 4: Reference base modes for the mature cattle, goats and sheep sub-models for evaluating sustainability of the low-input ruminant farming system in Eastern Cape Province, South Africa

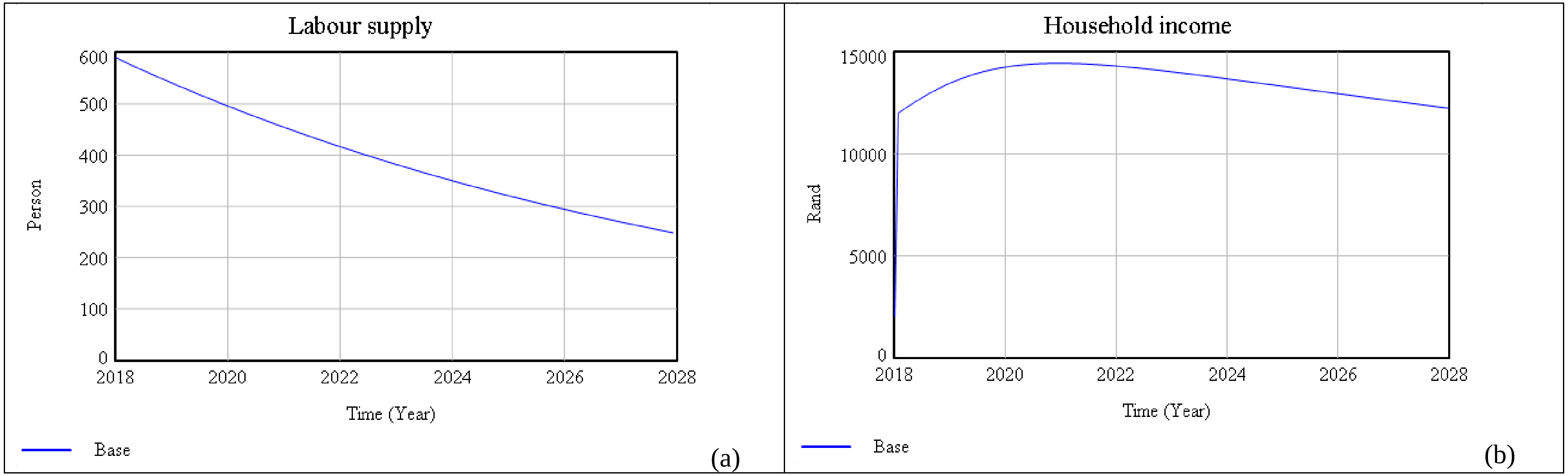


Figure 5: Reference base modes for the labour supply (a) and household income (b) sub-models for evaluating sustainability of the low-input ruminant farming system in Eastern Cape Province, South Africa

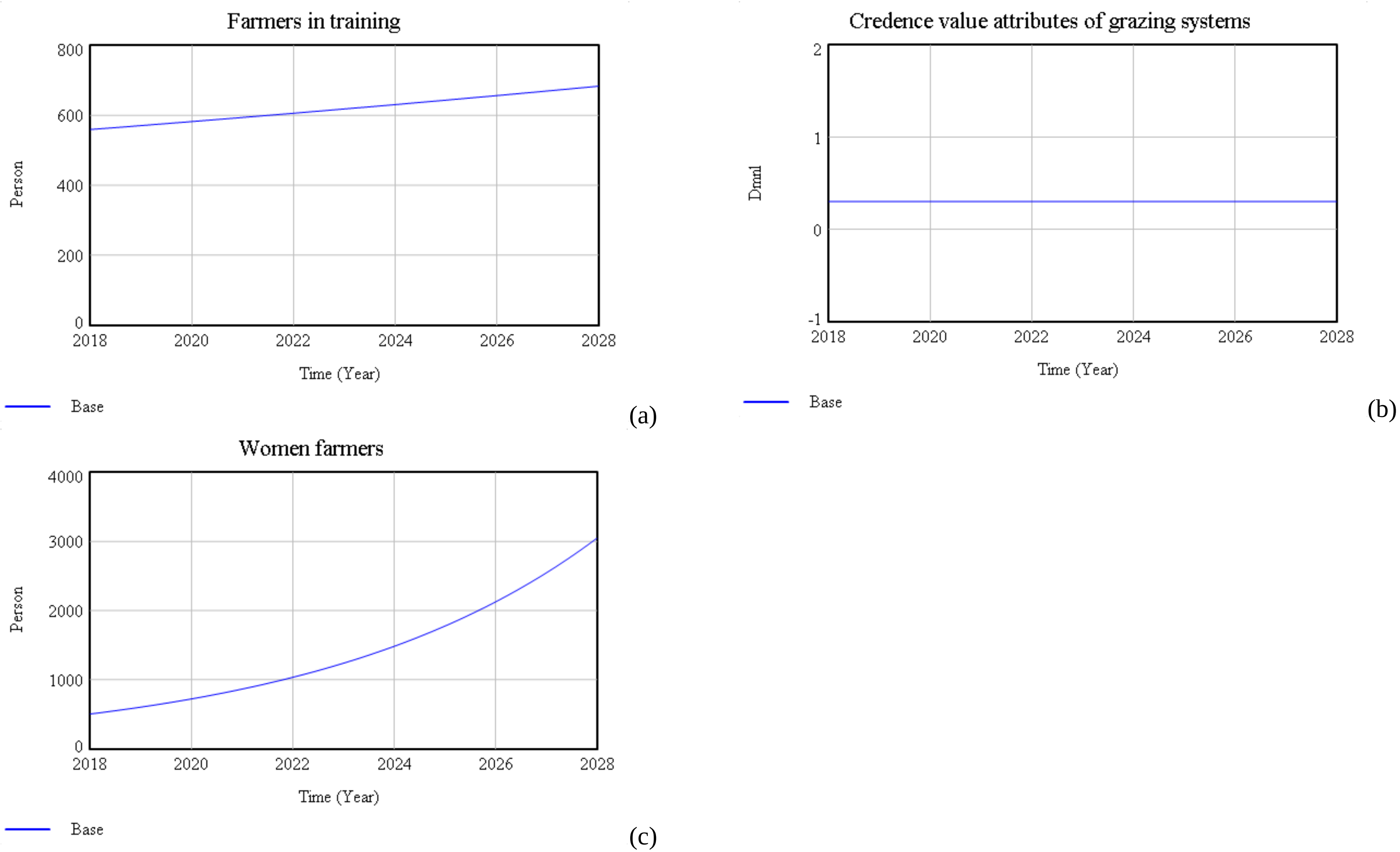


Figure 6: Reference base modes for the farmers in training (a), credence value attributes of grazing systems (b) and women famers (b) sub-models for evaluating sustainability of the low-input ruminant farming system in Eastern Cape Province, South Africa

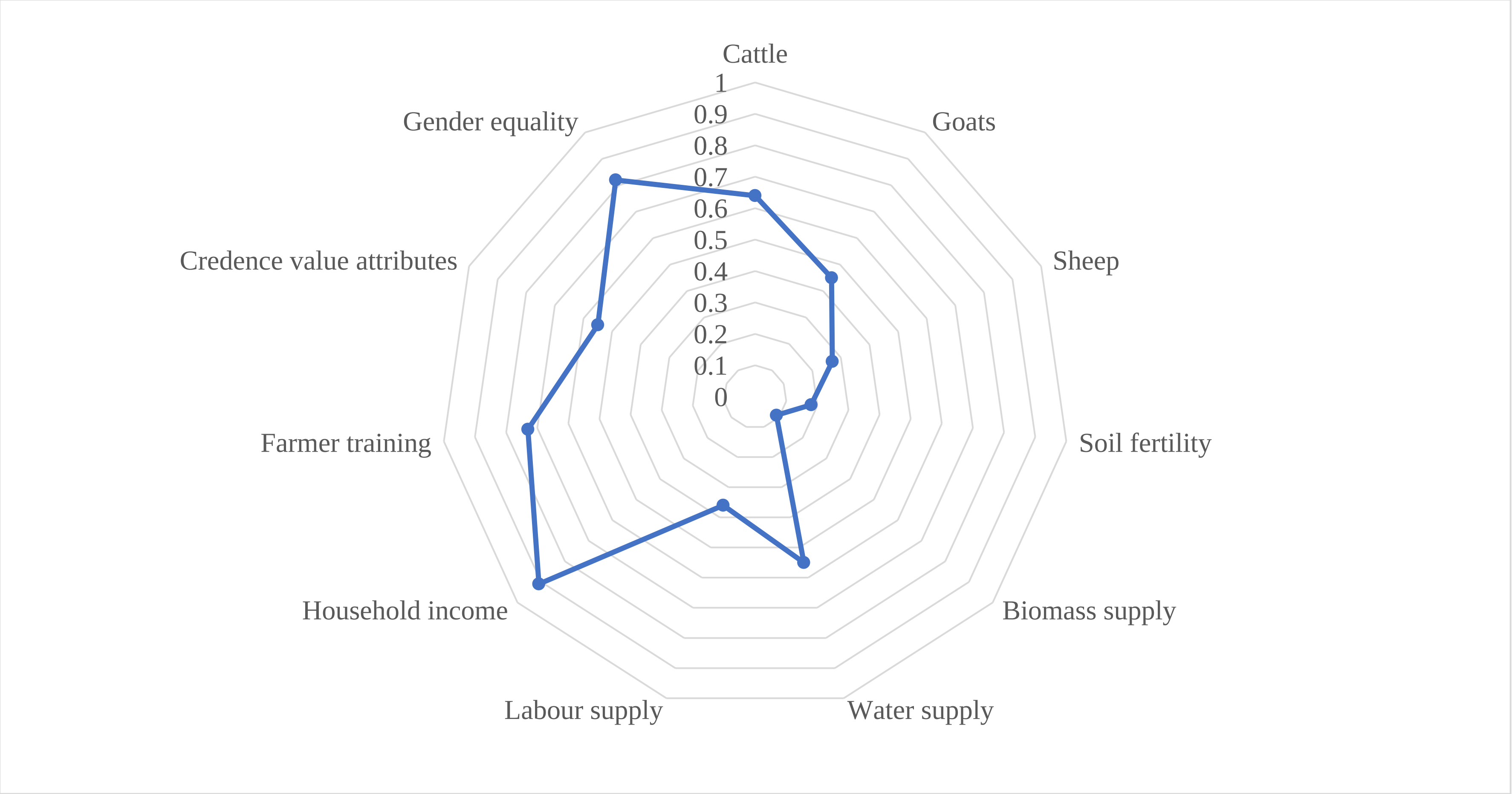


Figure 7: Index values for key model parameters to evaluate sustainability of low-input ruminant farming system in Eastern Cape Province, South Africa