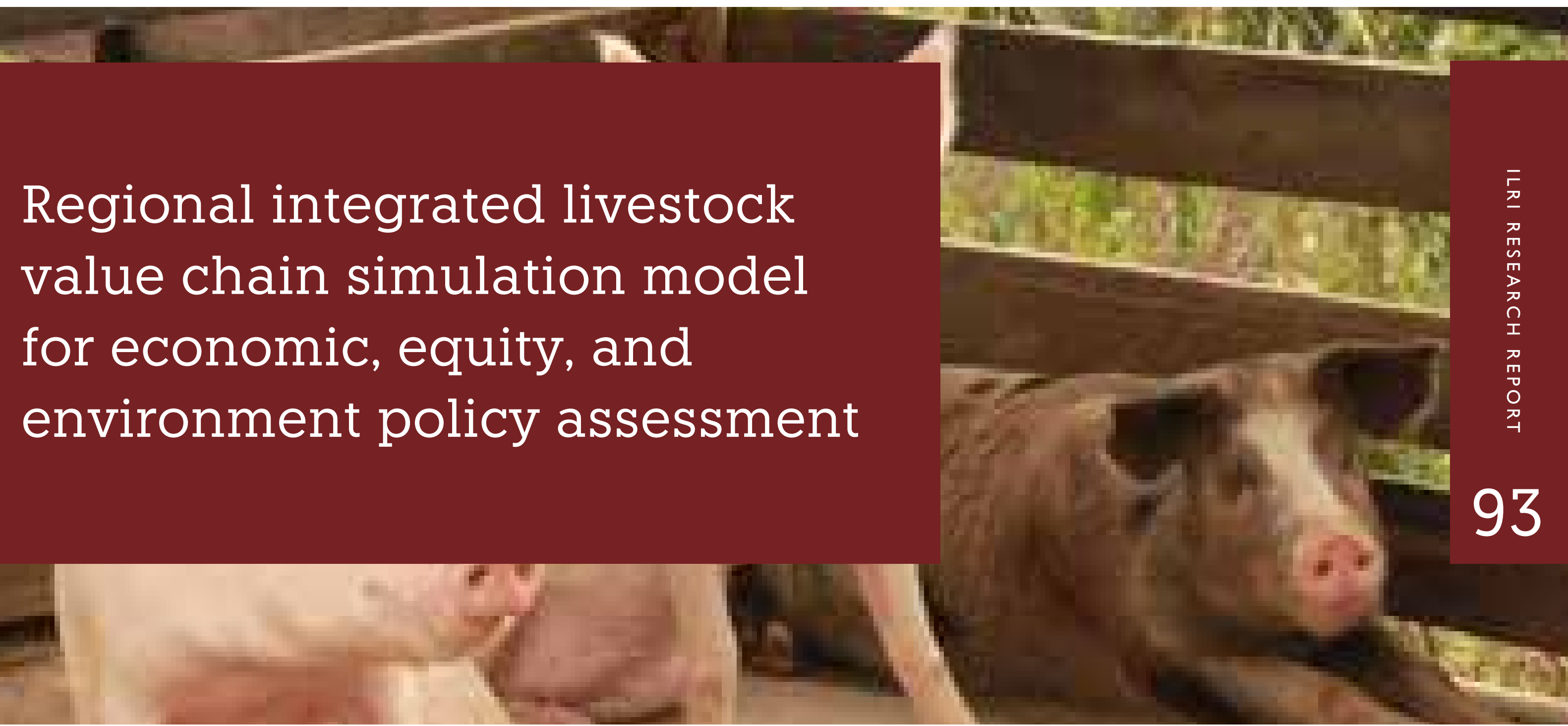

Regional integrated livestock value chain simulation model for economic, equity, and environment policy assessment

ILRI RESEARCH REPORT

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Regional integrated livestock value chain simulation model for economic, equity, and environment policy assessment

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Acronyms and abbreviations

AI	Artificial Insemination
ASF	African Swine Fever
ASF-LVC	Animal-Sourced Food Livestock Value Chains
CRP	CGIAR Research Program
FMD	Foot-and-Mouth Disease
GNR	Global Nutrition Report
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
LMP	Livestock Master Plan
LSIPT	Livestock Sector Investment Policy Toolkit
SD	System dynamics
SSA	Sub-Sahara Africa
USD	United States Dollar
VCM	Value chain mapping

1 Introduction

Approximately 1.5 billion people around the world, including about 75% of the world's poorest, are engaged in smallholder agriculture (Ferris et al. 2014). Livestock plays a key role in providing income to rural households, directly supporting the livelihoods of about one billion poor smallholders in the developing world (Smith et al. 2013; Mayberry et al. 2017). Livestock provides multiple goods and services including draught power, meat, eggs and milk, and they are inflation-resistant, cash-convertible assets (Dizyee et al. 2017). In addition to providing traction, which allows cropping in densely populated, mainly irrigated areas, livestock supply nutrients in these and other mixed crop-livestock systems, especially in sub-Sahara Africa (SSA).

Smith et al. (2013) and Haddad et al. (2016) estimated that in the coming decades, population growth, urbanization and income growth, especially in developing countries, will substantially increase the demand for animal-sourced foods (ASFs). The need to upgrade smallholder producers in the developing world to meet the expected growth in demand for ASFs and to raise income for smallholders through sustainable development and intensification is crucial (Upton 2004; McDermott et al. 2010). There is ample evidence (see Bahta and Malope (2014); Temoso et al. (2016); Asante et al. (2017)) that the productivity (e.g. yield) of livestock systems in developing countries are not efficient. This suggests, to some extent, that the expected future demand for ASFs could be met by closing yield gaps of existing livestock production systems through better animal husbandry and improved production technologies.

At the same time, much of the literature on yield gaps focuses mainly on productivity at the farm level and ignores the roles of important intermediary and end market value chain actors. These actors and activities have a direct impact on farmer behaviour. Over the past decade, several quantitative value chain models in the livestock sector that attempt to address these issues have emerged, highlighting the temporal impacts of value chain interventions on different actors and their prospective feedback effects. These include models for beef (Naziri et al. 2015; Dizyee et al. 2017), goats (Hamza et al. 2014), fish (Hamza et al. 2014a), dairy (Dizyee et al. 2019), and pigs (Rich et al. 2018; Ouma et al. 2018) which are applied to examine issues of ***inter alia*** value chain upgrading, animal/fish health, and food safety.

While these value chain analyses have provided important insights, particularly on the need for holistic, chain-level solutions, their focus has primarily been on the economic impacts of different interventions. However, contextual factors that drive and influence value chains, particularly equity, post-farmgate food waste and contamination, and chain actor investment decisions that influence and are themselves influenced by market-focused investments, need to be considered. Moreover, there may be other non-economic impacts on or from the environment. Other economic dimensions such as employment effects, making value chains more nutrition-sensitive, and post-production losses have also not been fully addressed.

This research note attempts to bring together these often-disparate dimensions of value chain impacts and drivers into a unified analytical framework. The primary motivation for this work lies in the need to develop a generic conceptual framework that can be applied in value chain-based action research on different livestock products in different countries. Such an approach is essential to highlighting how changes in one segment of the value chain (e.g. closing yield gaps and unlocking constraints at production level) impacts other segments of the chain (e.g. intermediaries and marketers), while taking the larger system's contextual drivers and influences into account. This is critical to inform the next generation of Livestock Master Plans (LMPs), which highlight the current constraints and contribution of the livestock sector to national development objectives, assess investment priorities and prospective returns of targeted investments on the performance of the sector (Rich et al. 2019). Such an approach will improve the robustness of identified investments and highlight prospective trade-offs along economic, social and environmental dimensions.

2 Animal-sourced food livestock value chains (ASF-LVC): Methodology

2.1 Conceptual framework

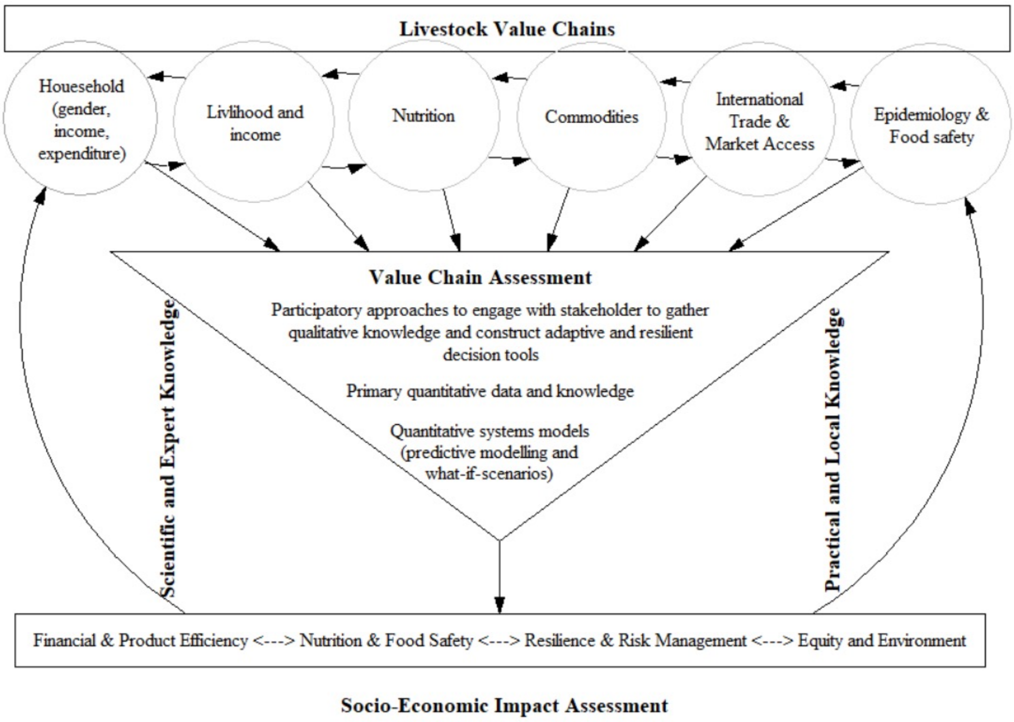
The conceptual framework here involves a series of interlinked steps that combine traditional value chain assessment with systems modelling protocols and a more holistic, modular approach towards modelling the different dimensions of the Animal-sourced Food Livestock Value Chains (ASF-LVC). Figure 1 illustrates our proposed framework. The upper side of figure 1 focuses on the contextual drivers and different elements that affect the livestock value chains. It consists of listing different livestock commodities sourced locally or globally (international trade) (Morgan et al. 2019) and key factors that influence the ASF-LVC such as policies on food safety (Hoffman et al. 2019), nutrition (Peña and Garrett 2018), staple commodities (National Academy of Science 1975; Venskutonis and Kraujalis 2013), and household income and food choices (Dzanku 2019; Lusk 2019). Depending on the aim of the study (e.g. nutrition intervention, access to an international market, gender and youth equity, food safety, etc.), a commodity or a group of commodities with similar production and market characteristics can be selected for the second stage, more detailed, assessment.

There are four stages of the ASF-LVC conceptual framework. The first stage is a listing of ASFs consumed in the targeted study region. This includes identifying key livestock value chains within ASF systems. Data on the ASF list can be obtained from secondary sources (e.g. FAOSTAT) and primary data sources (Rich et al. 2019). For example, FAOSTAT provides national-level livestock and ASF trade overview, while livestock data frameworks such as the Livestock Sector Investment Policy Toolkit (LSIPT) highlights targeted local production systems. Once the key commodities that contribute to ASF-LVC have been listed, a more targeted assessment to map specific value chains (e.g. cattle, small ruminants, chicken, etc.) can unlock value chain structures, opportunities, constraints and performance.

The second stage of ASF-LVC includes a standard value chain mapping (VCM) exercise and assessment (figure 1 – middle part). VCM consists of mapping the actors who participate in the production, distribution, marketing and sale of a product. Depending on the complexity required and objectives of the study, VCM could also include information related to the flow of products and their volume, costs and margins at different stages, added value, the flow of information and knowledge, type of relationships and linkages, number of actors by gender and generation, number of workers per actor, etc. Value chain analysis would begin by mapping the chain actors and their associated functions to understand the structure of the chain, its strengths and weaknesses relative to infrastructural, financial, institutional and social capital endowments.

The third step of ASF-LVC analyses and maps as overlays a mix of products traded, volumes and marketing margins at different nodes of the chain. These three steps provide the framework to characterize the underlying patterns of comparative and competitive advantages, if any, for producers, processors and marketers, and evaluate the existence of opportunities and potential for investment scenarios for upgrading of primary product practices and value addition processes across the chain. Hence, the central purpose of upgrading is to overcome the underlying constraints value chain actors face and capture market opportunities. The degree to which information and knowledge are shared and rewarded determines participants' ability to upgrade.

Figure 1: Integrated livestock value chain conceptual framework



The fourth step of ASF-LVC moves value chain assessment from a qualitative and descriptive assessment to a dynamic simulation modelling platform using a system dynamics (SD) modelling approach. This allows researchers to conduct ***ex-ante*** impact assessment and what-if-scenario assessment of different policy intervention scenarios. Such an approach will enable policymakers to evaluate the likely impact of interventions on specific value chain actors as well as on whole chain performance (e.g. see Dizyee et al. 2020; Dizyee et al. 2019; Ouma et al. 2018, Dizyee et al. 2017). SD models provide qualitative and quantitative outputs. The initial steps of SD models offer qualitative results on the problem under study, identify causal factors that influence these problems (i.e. feedback loops and circular causalities), and highlight policy interventions to address the problem under study. Qualitative results provide big picture insights to policymakers on the causes of the problem under study and potential policy options to address them.

Quantitative SD model outputs provide more robust scenario (or trade-off) analysis on the performance of value chain actors (i.e. changes in value chain actors' profit and sector contributions to the economy) under different scenarios. As an example, tables 1 to 3 present results from previous SD models for a case study of the pig/pork value chain in Uganda (Ouma et al. 2018); cattle/beef value chains in Botswana (Dizyee et al. 2017); and the dairy value chain in Tanzania (Dizyee et al. 2019), respectively, under baseline and different policy interventions.

Table 1 summarizes the financial performance of the different pig value chain actors in Uganda under different policy scenarios relative to the baseline scenario, based on a 15-year simulation time horizon (Ouma et al. 2018). Model results revealed that producers lose out from scenario 2 (biosecurity interventions), through gross margins that are 6.3% lower per year relative to the baseline due to the high investment cost of biosecurity to control ASF. Butchers, traders, collectors and wholesalers, on the other hand, all benefited through higher gross margins that rise by about 3.5 to 7% per year compared to the baseline. The higher margins accruing to various value chain actors, apart from producers, resulted from the more stable supply of pigs as a result of implementation of biosecurity practices by farmers, leading to a reduction in mortalities and transaction costs.

Table 1: Average annual change of pig value chain actors' cumulative profit in Uganda relative to baseline (based on a 15-year model run). (Source: Ouma et al. 2018).

	Pig value chain actors[1]				
Scenario	Producers	Butchers	Traders	Collectors	Wholesalers
Scenario 2 Vs 1	-6.3%	7.1%	9.2%	7.6%	7.0%
Scenario 3 Vs 1	8.4%	4.7%	8.1%	6.6%	3.5%
Scenario 4 Vs. 1	3.7%	12.7%	20.9%	16.9%	10.0%

Notes: Scenario 1: baseline; Scenario 2: ASF biosecurity implementation; Scenario 3: Pig business hub; Scenario 4: coupling of ASF biosecurity and pig business hub intervention. [1]% sign means per cent change relative to baseline (e.g. -6.3% in the first row means that producers under scenario 2 are making 6.3% less profit relative to baseline, scenario 1.

The business hub (scenario 3) resulted in positive margins for all value chain actors, including producers (3.5 to 8.4% per year). In this scenario, producers benefit from higher prices and a more stable pig supply due to lower mortalities. Other value chain actors benefit from stable pig supplies in the market and economies of scale due to bulk purchases.

The combined effects of the two interventions (scenario 4) result in higher pig supplies and positive margins for all value chain actors. Producer margins change positively by about 4% per year, relative to the baseline. Producer margins in scenario 4 are lower than scenario 3 due to the higher costs associated with implementing biosecurity control measures.

Model results summarized in table 2 present results for the accumulated profits of each beef value chain actor in Botswana over a 15-year period (discounted by 5.6%, which is the average annual inflation over recent years), under different policy interventions to control for foot-and-mouth (FMD) disease and market liberalization (Dizyee et al. 2017). Table 2 expresses value chain actor profits as percentage departures from the baseline (scenario 1 – business as usual), as well as presenting a comparison of scenarios 2 (market liberalization), 3 (business as usual plus FMD control) and 4 (market liberalization plus FMD control).

Table 2: Beef value chain actor financial performance in Botswana relative to baseline scenario (Source: Dizyee et al. 2017)

Runs	Producers	BMC	Feedlots	Traditional Butchers	Modern Butchers and Retailers	Whole Chain Performance1
Scen. 2 Vs. 1	84%	-379%	-28%	1%	-5%	17%
Scen. 3 Vs. 1	26%	101%	9%	0.5%	4%	19%
Scen. 4 Vs. 1	141%	-399%	-26%	1%	-3%	43%
Scen. 4 Vs. 3	NA	NA	NA	NA	NA	20%

Notes: Scenario 1: baseline; Scenario 2: market liberalization; Scenario 3: business as usual and FMD control; Scenario 4: coupling market liberalization and FMD control. [1]% sign means per cent change relative to baseline (e.g. 17% in the first row means scenario 2 is 17% more profitable than baseline or scenario 1.

Table 3 illustrates model results from a study of dairy value chains in Tanzania's Kilosa district with a focus on economic and non-economic performance measures of chain actor milk production, accumulated profits, milk consumption in producer households, percentage of cross-bred cattle, and milk traded to post-farmgate value chain actors (Dizyee et al. 2019). The Tanzania dairy model measures performance indicators over multiple periods which offers policymakers a tool to track the performance of different policy interventions over mid- and long-term timeframes. Similarly, the model also shows trade-offs between different performance indicators (e.g. profit and milk consumption) which provides policymakers with a quantitative assessment of competing priorities among different outcomes of policy interventions.

Ex-ante impact assessment results, as shown through case study examples in tables 1 to 3, enable policymakers to evaluate the likely impact of interventions considering the initial investment costs (e.g. artificial insemination (AI), animal health and biosecurity) and time lags until adopters start to obtain returns from their investment. This is important as some interventions (e.g. AI and health and biosecurity, etc.) are expensive relative to producer incomes and of high risk (i.e. AI success rate is not guaranteed, the survival rate of newborn cross-bred calves depends on animal health and veterinary services, yield genetic potentials of cross-bred cattle depend on the availability of sufficient livestock feed, strong animal health and biosecurity do not always prevent disease outbreaks and guarantee market access). The proposed *ex-ante* impact assessment platform estimates the likely time where adopters (producers) receive positive returns on investment, the timeframe (in years) where producer income might decline due to initial costs of investment, and equity (distribution of losses and gains) issues among different chain actors. The *ex-ante* impact assessment outcomes thus allow policymakers (at public and private sector levels) to better understand the constraints of adopting different production technologies which enables them to investigate potential solutions to increase sustainable adoption of tested production technologies.

Table 3: Cumulative changes of producer profits and other key variables (2025 and 2035) (Source: Dizyee et al. 2019)

Scenarios[1]	Percentage change in cumulative (by the end of 10 yr simulation in 2025)					
	Milk production	Cumulative profit	Milk consumption[2]	Improved crossbreed (%total population)	Milk traded to a market hub (litre)	Milk traded to processors (litre)
2 vs.1	4%	-14%	4%	31%	no change	no change
3 vs.1	4%	-11%	4%	31%	29,166	23,339
Percentage change in cumulative (by the end of 20 yr simulation in 2035)						
2 vs.1	67%	1%	34%	73%	no change	no change
3 vs.1	57%	133%	30%	67%	2,523,843	2,019,263

[1]Scenario 1: Baseline; Scenario 2: Artificial insemination; Scenario 3: Artificial Insemination + Market Hub. [2]Consumption includes consumption at producer households and given away (non-commercial).

To see how all chain actors can benefit, it is important to understand the market structures and conduct and the innovation systems needed to upgrade current practices and technologies to continuously enhance productivity, market efficiency, livelihood and nutrition. The last stage of ASF-LSV is, therefore, an essential approach to evaluating the value chains by using a set of key performance indicators (figure 1 – bottom part), considering the prevailing contexts surrounding each study. Such an approach would ensure comparability of lessons learnt from each country and application of coherent sets of methods and tools.

2.2 Performance measures in value chain analysis

Performance of the value chain is what we are ultimately interested in, though this concept is multi-dimensional. At its most basic level, value chain performance measures the extent to which participants of the value chain achieve their objectives within their individual operation with an aim of delivering value to end-users. However, value chains can perform along with a host of other developmental and investor priorities that can be at odds with individual chain actor goals. This section discusses and lists specific value chain performance metrics and, using systems thinking language and concepts, provides a graphical illustration of the means to measure them.

The measures are grouped along the following four performance dimensions: (1) financial and product efficiency, (2) nutrition and food safety, (3) resilience and risk, and (4) equity and environment. All these dimensions influence the competitiveness of the value chain. The degree of importance of these performance dimensions depends on the issue and research question at hand. Furthermore, some performance metrics apply to more than one dimension. The extent to which the whole value chain delivers value depends on various factors including coordination along the value chain, information flows within and across value chain nodes, the capacity of value chain participants to respond to opportunities and threats, and the distribution of power in the value chain. Some measures will apply more at certain stages of the value chain while others will apply for all value chain actors.

2.2.1 Financial and product efficiency performance

The primary goal for value chain participants is to generate income. Financial performance measures the return to taking a risk, return to management, and reward to innovation and investment. For value chain participants to remain viable, healthy financial performance is important. Besides traditional measures of profit, the amount of value created by the value chain and its share among the VC actors are important indicators of financial performance (Dizyee et al. 2017; Ouma et al. 2018). These financial performance metrics include income-related measures such as profit rates, total costs, accumulated profit, profit from by-products, service provision (e.g. transport and labour), and the whole of chain profit (all value created throughout the value chain) (see figure 2 below).

Efficiency relates to how successful the value chain is at delivering value to its end-users. These relate to measurements of lead time, inventory management and transaction costs. Efficiency improvement can occur at any node of the value chain. However, its impact might be limited to how other nodes of the chain respond to such changes in efficiency and how returns to investment in value chain efficiency are distributed among chain actors. That is, if returns to investment in a more efficient and resilient supply chain is not internalized, then it is unlikely for actors at specific nodes (e.g. producers) of the chain to invest. For example, in table 1, model results showed that producer investment in better animal health management had a negative impact on their own profits which makes it less likely for producers to invest in a more efficient supply chain. This was despite such a strategy improving the financial performance of other chain actors.

Figure 2: Key elements of financial and efficiency performance measures.

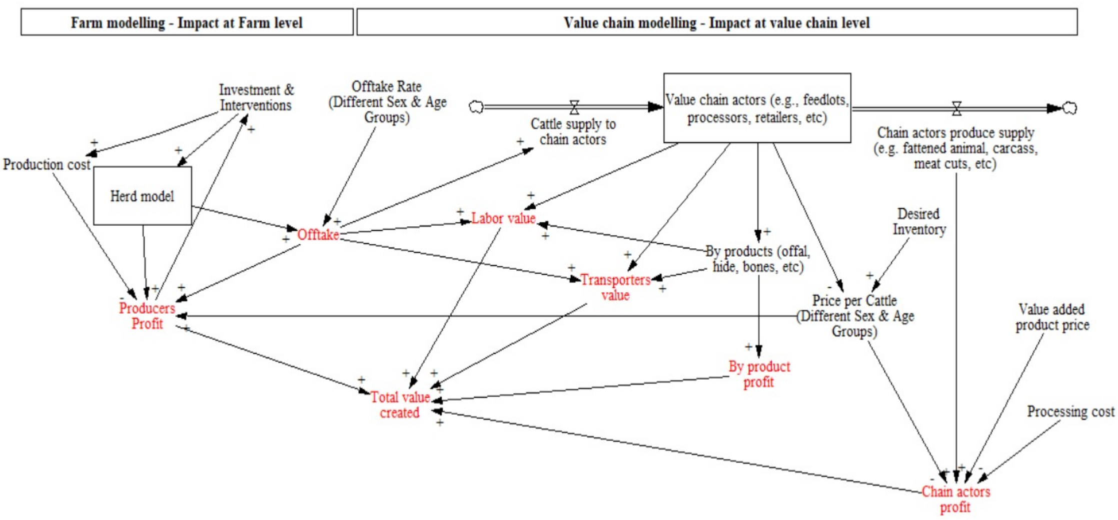
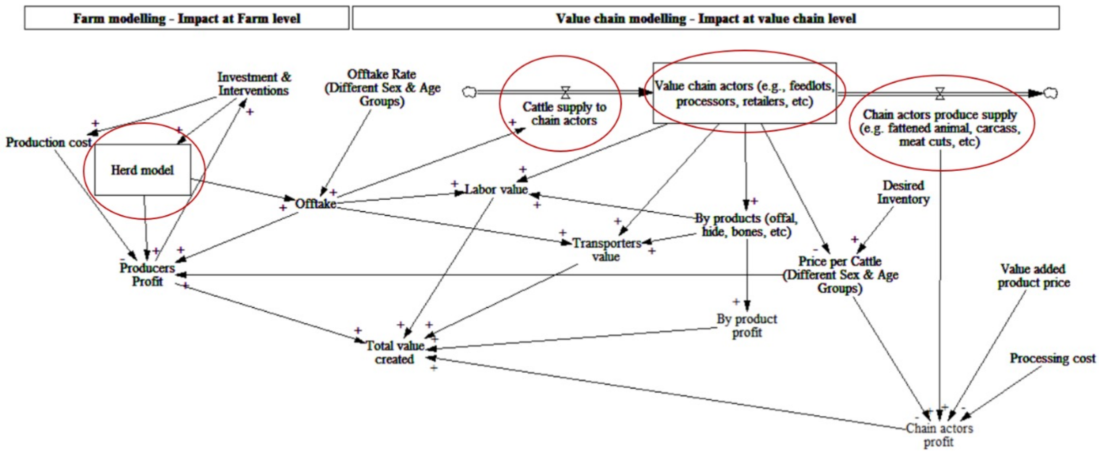


Figure 2 presents a generic conceptual model structure, using system dynamics concepts to measure financial and efficiency performance indicators. These indicators are linked together. That is, an improvement in financial performance (e.g. producer profits) would likely increase investments at the farm level, which is likely to increase profit, and vice versa. Similarly, value chain financial and efficiency performance are interlinked throughout the value chain. That is, investment on one side of the chain is linked to the capacity and capability of other chain actors (e.g. an increase in efficiency at farm level might not be practical (even if technically feasible) if there is no extra demand for the product and post-farm gate value chain has limited access to markets).

2.2.2 Nutrition and food safety

The goal of the value chain is to deliver suitable products to consumers that are economically viable, nutritious and safe. The economic viability performance measure is described in section 2.2.1. Nutrition and food safety performance indicators are measured by identifying food loss and food safety hotspots along the value chain (see figure 3 which highlights the likely places where food loss and contamination in a value chain could occur), and added ingredients (e.g. salt, oil, cooking methods) to end products. Food losses, contamination and processing methods could potentially undermine nutritional integrity and food safety of the products delivered through value chains. Figure 3 presents the nutrition and food safety hotspots along the value chain.

Figure 3: Nutrition and food safety hotspots along the value chain.



Food loss and contamination can occur at each node (e.g. producers, processors, retailers, etc.) of the value chains. Food loss and contamination, in addition to their negative impact on the value chain's financial and efficiency performance, can result in nutrition loss. This can occur either through direct food waste (i.e. food thrown away due to contamination or lost during the transaction through the value chain) or consumer illness following consumption of a contaminated product. Nutritional losses can also arise from limited access to healthy products due to various logistical or other impediments which hinder consumers from purchasing the products (Cooper et al. 2021). Similarly, processor practices can also change the nutritional content of food products – addition of ingredients such as preservatives and oil might compromise the nutritional integrity of food products.

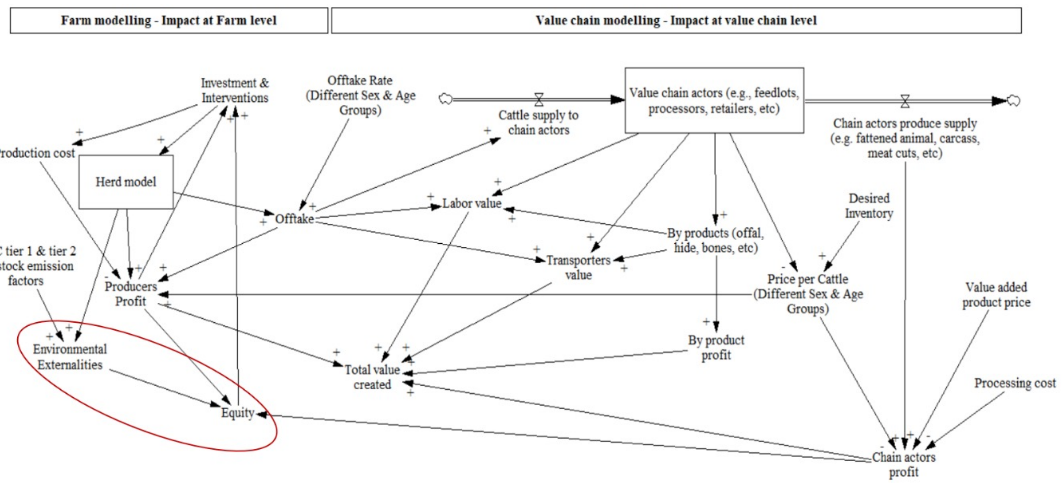
2.2.3 Resilience and risk management

Risk and uncertainty are key issues that have an impact on value chain actor operations, decision-making and performance (Aboah et al. 2019). The sustainability and long-term performance of a value chain is strongly influenced by its resilience to external shocks (e.g. disease outbreaks, drought), including exposure to risk within and along the value chain. Thus, estimating the impact of external shocks such as disease outbreaks on value chain actors and whole chain performance is important (Dizyee et al. 2017; Ouma et al. 2018). Tables 1 and 2 above present the impact of disease outbreaks of African swine fever (ASF) and foot-and-mouth disease (FMD), respectively, on different value chain actors and whole chain performance. Measuring the expected impact of external shocks such as disease outbreaks and different scenarios to prevent and control disease outbreaks enable policymakers to understand feasible disease management practices considering issues of equity and return on investment (see tables 1 and 2 of different value chain actor performance under different disease management scenarios in pig/pork and cattle/beef value chains in Uganda and Botswana, respectively).

2.2.4 Equity and environment

Equity consideration includes a broader social evaluation of the value chain. This dimension relates to issues of fairness on how benefits flowing from the value chain are shared among its participants (both direct and indirect), as well as potential positive spillover effects to the wider economy in the form of increased employment, thus potentially reducing poverty. There can also be negative externalities related to the environment through how primary production and processing utilize the resource base, emissions of toxic substances, including greenhouse gases (GHGs) that can contribute to environmental contamination. We measure equity performance in terms of the distribution of value (in financial terms) among different chain actors and overall chain performance (see tables 1 and 2) and competing priorities between nutrition (e.g. consuming produce at household level) and marketing. Similarly, we also measure negative externalities that are generated because of value chain activities in the form of environmental performance which will be measured based on IPCC tier 1 and tier 2 emission factors relevant to livestock in specific study regions to estimate the GHG emission under different scenarios of value chain interventions (Dahlanuddin et al. 2017). Figure 4 illustrates a sample model structure for measuring equity and environmental externalities along the value chain.

Figure 4: model structure for equity and environmental externalities along the value chain.



Individual actors along different stages of the value chain primarily focus on their individual operations and goals. However, value chains do not operate in a vacuum, and while there is no joint objective by value chain participants to address social problems, it is important to evaluate the broader impact of the value chain. Some measures include the potential improvement of livelihoods of particular groups such as women and youth, and differential impacts related to income and employment effects. See the appendices for more details about module descriptions and module equations that specify some of these issues in more detail as follows: Appendix A: Module description; Appendix B: Beef and dairy module equations; Appendix C: Goat module equations; Appendix D: Sheep module equations; Appendix E: Pig module equations; Appendix F: Post-farm-gate value chains module equations; Appendix G: Markets module equations; Appendix H: Preliminary household module equations; and Appendix I: Forage module equations.

3 Discussion

Recent calls to challenge the status quo of food systems to focus on food security and nutrition have become an emerging field to achieve the United Nations Sustainable Development Goals (Fanzo et al. 2020). This includes shifting strategies to end hunger and eradicate malnutrition to broader food systems thinking and policymaking (Haddad et al. 2016). Similarly, other studies on nutritionally-sensitive value chain interventions have pointed out impact pathways to tackle the triple burden of malnutrition (see Ridoutt et al. (2019) for a recent literature review). The 2020 Global Nutrition Report (GNR) indicated that failure to address food insecurity and various forms of malnutrition will generate substantial problems and this could hinder the goal of sustainably meeting future food and nutrition security. Such advocates of a food systems approach to policymaking rightfully promote the need to change food systems to address future food and nutrition security. However, most of these studies focus on a top-down policymaking approach at global and national levels which ignores the microeconomic implications of such policies which our modelling framework aims to address.

Such a top-down policymaking approach alone is unlikely to effectively change food systems and incentivize agricultural systems to produce a greater variety of healthy foods relative to staple commodities. This is because changes in food systems will need public-private initiatives and partnerships at the value chain level to ensure feasible policy options (GNR 2020) and avoid value chain failure (Baker et al. 2017). This research note complements the food systems research approach by integrating livestock value chains within food systems and an impact assessment rubric for policymakers to conduct analysis at the livestock value chain and sector level. Furthermore, our framework includes multiple performance indicators such as financial and product efficiency performance, equity (environmental externalities, gender, youth, distribution of value among different chain actors), nutrition and food safety, resilience and risk management that often compete against each other. Measuring and considering these performance indicators (figure 1 – bottom part) is essential to ensure a holistic assessment of food systems policymaking to promote viable and feasible policy options, thus avoiding policy resistance by powerful value chain actors (e.g. processors, retailers, exporters, and importers) due to loss of market share and profit that could eventually lead to policy failure (Dizyee et al. 2017; Dizyee et al. 2019).

Other non-financial performance indicators included in our framework are also crucial to deliver on policies that aim to change livestock value chains to provide healthier and more varieties of food products to consumers. These include performance indicators that highlight the role of gender and household income on food choices. Dzanku (2019) reported that off-farm income received by female-headed households in poor regions in six African countries has a stronger association with food security relative to their male-headed household counterparts. Similarly, higher household income and food expenditure are associated with higher diet variety and consumers' preference instability (Lusk 2019). This indicates that the gender dimension of household food expenditure will have a substantial impact on the demand for household food products which could play a crucial role in reshaping food systems from the demand side (bottom-up) through policies that aim to empower women and enhance livelihoods of low- and middle-income households in developing countries.

Similarly, risk factors such as food safety and animal health issues play key roles in producers' and value chain actors' livelihoods, consumers' food choices, and nutritional value of the products they consume. Food safety hazards cause foodborne diseases that result in substantial health issues and economic loss in low- and middle-income countries (Hoffmann et al. 2019). Similarly, food safety hazards and animal diseases limit marketability of products, especially access to high-end markets which constrains the economic potential of agriculture and the livestock sector (Dizyee et al. 2017). Furthermore, disruption in food supply chains due to animal disease will likely result in volatility in the food supply which will have a negative impact on food and nutrition security.

All components of food value chains are interlinked. Shocks which disrupt the system and undermine food and nutrition security can come from either the supply or demand side (Barrett 2020). Similarly, performance indicators of value chains are interlinked. Measuring the impact of an intervention that aims to enhance international trade and market access in trade volume and financial terms alone will be deemed incomplete without considering equity issues (e.g. distribution of value among chain actors, environmental externalities). Likewise, a nutritionally sensitive value chain intervention might not be feasible if it does not consider the financial performance of value chain actors (Cooper et al. 2021). The nexus among interventions in food systems (e.g. gender empowerment, nutrition and livelihood improvement, food safety, animal health, international trade and market access), performance indicators (financial and product efficiency performance, equity and environment, resilience and risk management, and nutrition and food safety), feedback loops (circular linkage) among interventions and performance indicators are crucial for any successful policy intervention in food value chains.

In a similar vein, policy interventions in food chains are unlikely to be feasible and effective unless they are based on scientific evidence and allow for engagement of various stakeholders that are affected, directly or indirectly. Our framework (figure 1) relies on existing scientific methods to extract available data (i.e. secondary sources – e.g. FAOSTAT; and from primary data sources – e.g. LSIPT assessments (Rich et al. 2019)). Participatory processes also serve as sources of local and practical knowledge in food systems and can contribute to the design of feasible policy interventions (see Lie et al. (2017) and Rich et al. (2018a)).

4 Conclusion

Our study provides a framework to bring different elements of livestock value chains and their performance indicators together in a unified conceptual framework. A key contribution of our approach is the inclusion of a set of interlinked performance indicators that, directly and indirectly, impact individual value chain actor performance, food and nutrition security, and contribute to shaping the food systems environment. We hope that this conceptual note will enable a more holistic assessment of policy interventions to improve the food value chains by simultaneously considering various but interlinked performance indicators that are based not only on scientific data and expertise, but also on local and practical knowledge of stakeholders within food systems.

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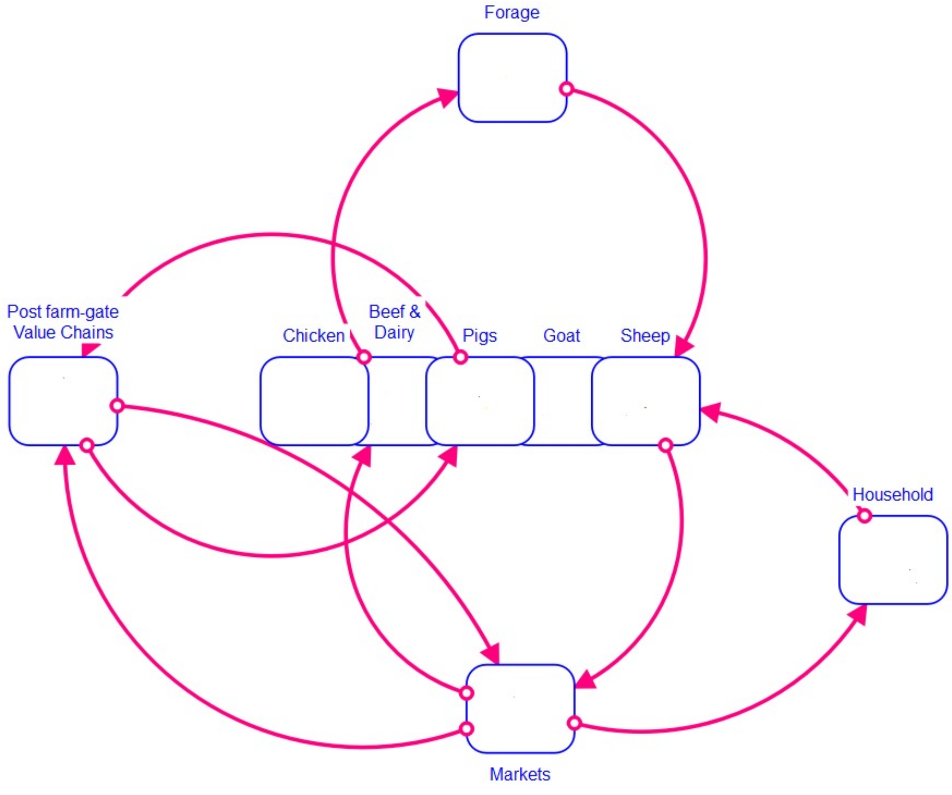
6 Appendices: Module description and equations

Appendix A: Module description

Figure 4 (page 14) shows an aggregated portrayal of the model. Our model includes various modules (Figure A.1) that represents different herds of livestock (e.g. beef, dairy, chicken, goat, pigs, and sheep), market (i.e. supply, demand, and price-setting), post-farmgate value chains (e.g. product flow to and financial performance of wholesalers, processors, retailers, etc.), forage and environment (i.e. livestock feed), and equity (e.g. household income and expenditure, and value chain actors financial performance).

In figure A.1., the modules (boxes) are aggregated representations of livestock herds, markets, forage, post-farmgate value chain actors, and household finance. The modules of beef and dairy, goats, sheep, and pigs represent herd models that include stocks of producers' livestock which are inventories of animals at different age cohorts from gestation, calves, adults to breeding stock (appendices B, C, D, and E shows herd model equations for beef and dairy, goats, sheep, and pigs, respectively).

Figure A.1: Interaction among different modules.



Post-farm-gate value chains include livestock trade and financial performance of post-farm-gate value chain actors and livestock (and meat) inventories held by different value chain actors— e.g. wholesalers, traders, processors, butchers, retailers, etc. (Appendix F shows the model equation for post-farm-gate value chain actors product flow and financial performance). Post-farm-gate value chain actors interact with producers (i.e. herd model) by means of livestock trade and financial transaction which is determined by market dynamics. Changes in the market module also determine the volume of product flow to post farm-gate value chain actors and their financial performance.

The market module sets supply and demand by utilizing the feedback effect of price information in all market channels. The inventory decisions by downstream actors' influence prices, which subsequently affect the incentives for producers to market products (animals, carcass, and meat) via the various market channels. The magnitude and timing of price effects depend on the price elasticities of supply and demand, and the lags inherent in decision-making based on new information (Appendix G shows the equation for a market module). The interaction between the market module and herd models is through the producer's performance based on changes in the market and investment decisions. Similarly, changes in the market impact the household model by means of determining the profitability of the livestock sector. Income from farming activities along with off-farm income consists of producers' income which they use for essential expenditure such as food, clothes, school fees and other household expenditure which determines investment decisions on livestock (i.e. if money remains after all essential expenditures) (see appendix H for household module equations).

The forage module represents the environmental variables such as the amount of pasture available on pasture lands. Pasture resources increase (and decrease) through the natural growth (and natural decay and consumption—feed consumption) which in turn depends on rainfall, land and livestock units per hectare of land (Appendix I shows equations of pasture module). Feed resources and total livestock population determine resource consumption per livestock which affects livestock fertility, mortality, and herd size.

Appendix B: Beef and Dairy module equations

Actual AI Used(t) = Actual AI Used(t - dt) + (Actual Used AI Over Time - Actual Used AI Exit) * dt

INIT Actual AI Used = 0

INFLOWS:

Actual Used AI Over Time = Actual AI

OUTFLOWS:

Actual Used AI Exit = DELAY(Actual Used AI Over Time, 1)

Adult Male(t) = Adult Male(t - dt) + (Becoming Adult Male - Adult Male Death Rate - Adult Male Slaughter Rate) * dt

INIT Adult Male = 674 {cattle}

INFLOWS:

Becoming Adult Male = Preadult Male/Time to Mature {cattle/week}

OUTFLOWS:

Adult Male Death Rate = Adult Male*Adults Fractional Death Rate {cattle/week}

Adult Male Slaughter Rate = Adult Male*Adult Male Sale Rate {cattle/week}

Calves(t) = Calves(t - dt) + (Calving - Calves Death Rate - Becoming Preadult Male - Becoming Preadult Female) * dt

INIT Calves = 1256 {cattle}

INFLOWS:

Calving = DELAY3((Breeding Rate*Survival rate), Gestation Period) {cattle/week}

OUTFLOWS:

Calves Death Rate = Calves*Calves Fractional Death Rate {cattle/week}

Becoming Preadult Male = (Calves/Time to become Preadult)*Calve Male to Female Ratio {cattle/week}

Becoming Preadult Female = (Calves/Time to become Preadult)*Calve Male to Female Ratio {cattle/week}

Cumulative profit per year(t) = Cumulative profit per year(t - dt) + (Profit per week - Adjusted annualy - Discounting) * dt

INIT Cumulative profit per year = 0 {USD}

INFLOWS:

Profit per week = Producers Profit Over Time {USD/week}

OUTFLOWS:

Adjusted annually = PULSE(Cumulative profit per year,52,52) {USD/week}

Discounting = Cumulative profit per year*Avg inflation rate {USD/week}

Dry cows(t) = Dry cows(t - dt) + (Becoming Breeding Female + Drying - Breeding Stock Slaughter Rate - Breeding Stock Death Rate - Becoming Milk Producers) * dt

INIT Dry cows = 1802-800 {Cattle}

INFLOWS:

Becoming Breeding Female = Preadult Female/Time to Mature {cattle/week}

Drying = Milk Producing Cows/Lactation period {cattle/week}

OUTFLOWS:

Breeding Stock Slaughter Rate = Dry cows/Average Breeding Period {cattle/week}

Breeding Stock Death Rate = Dry cows*Breeding Stock Fractional Death Rate {cattle/week}

Becoming Milk Producers = Calving+Mixed breed dairy cattle.AI Calving {cattle/week}

Gestation Delay(t) = Gestation Delay(t - dt) + (Breeding Rate - Calving - Still born rate) * dt

INIT Gestation Delay = 1140 {cattle}

INFLOWS:

Breeding Rate = (((Dry cows+Milk Producing Cows)*Calves per parturition*Number of births per cattle per year*Fertilization Success Rate*Actual effect of profit on production)/52)-Mixed breed dairy cattle. AI breeding rate {cattle/week}

OUTFLOWS:

Calving = DELAY3((Breeding Rate*Survival rate), Gestation Period) {cattle/week}

Still born rate = DELAY3((Breeding Rate*Fractional Abortion Rate), Gestation Period) {cattle/week}

Milk Producing Cows(t) = Milk Producing Cows(t - dt) + (Becoming Milk Producers - Drying - Milk Producing Cows Death Rate) * dt

INIT Milk Producing Cows = 800 {cattle}

INFLOWS:

Becoming Milk Producers = Calving+Mixed breed dairy cattle.AI Calving {cattle/week}

OUTFLOWS:

Drying = Milk Producing Cows/Lactation period {cattle/week}

Milk Producing Cows Death Rate = Milk Producing Cows*Breeding Stock Fractional Death Rate {cattle/week}

Preadult Female(t) = Preadult Female(t - dt) + (Becoming Preadult Female - Becoming Breeding Female - Preadult Female Death Rate - Preadult Female Sales Rate) * dt

INIT Preadult Female = 1028 {cattle}

INFLOWS:

Becoming Preadult Female = (Calves/Time to become Preadult)*Calve Male to Female Ratio {cattle/week}

OUTFLOWS:

Becoming Breeding Female = Preadult Female/Time to Mature {cattle/week}

Preadult Female Death Rate = Preadult Female*Preadult Female Fractional Death Rate {cattle/week}

Preadult Female Sales Rate = Preadult Female*Preadult Female Fractional Sales Rate {cattle/week}

Preadult Male(t) = Preadult Male(t - dt) + (Becoming Preadult Male - preadult Male Sales Rate - Preadult Male Death Rate - Becoming Adult Male) * dt

INIT Preadult Male = 443 {cattle}

INFLOWS:

Becoming Preadult Male = (Calves/Time to become Preadult)*Calve Male to Female Ratio {cattle/week}

OUTFLOWS:

preadult Male Sales Rate = Preadult Male*Preadult Male Fractional sales rate {cattle/week}

Preadult Male Death Rate = Preadult Male*Preadult Male Fractional Death Rate {cattle/week}

Becoming Adult Male = Preadult Male/Time to Mature {cattle/week}

Producers Cumulative Profit(t) = Producers Cumulative Profit(t - dt) + (Producers Profit Over Time) * dt

INIT Producers Cumulative Profit = 0 {USD}

INFLOWS:

Producers Profit Over Time = ((Milk sales rate to individual consumers*Milk Price per Litre at Individual Consumers Market)+(Milk sales rate to traders*Milk Price per Litre at Traders Market)+(Milk Sales Rate to Milk market hub*Milk Price per Litre at Milk Collection Center))-Total Weekly Operational Cost {USD/week}

Actual AI = IF Artificial insemination success breeding rate = 0 THEN 0 ELSE Mixed breed dairy cattle.AI breeding rate/ Artificial insemination success breeding rate {unitless}
Actual effect of profit on production = MIN((DELAY3(Effect of profit on production,52)),1) {unitless}
Actual movement = SMTH3(Transhuman movement, 8) {unitless}
Actual Rainfall = (Annual Random Precipitation*Rainfall Seasonality)/52
Adult Male Sale Rate = 0.7/52 {1/week}
Adults Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
AI = 0 {unitless}
AI fractional success rate = 0.6 {unitless}
AI introduction time = IF TIME <156 THEN 0 ELSE 1 {unitless}
Annual Random Precipitation = RANDOM(200,1000,600)
Artificial Insemination Cost per Service = 18.3 {USD/AI}
Artificial insemination success breeding rate = Proportion of AI use*AI fractional success rate*Expected natural breeding rate {cattle/week}
Average Breeding Period = 416 {week}
Average Cost of Feed Concentrate per Household = 155.1/52 {USD/household/week}
Average Cost of Purchasing Fodder per Household = 277/52 {USD/household/week}
Average Cost of Using Crop Residues per Household = 16/52 {USD/household/week}
Average Cost of Using Other Farmers Bull per Service = 1.5 {USD/household/year}
Average Expenditure per Household on Animal Health = 326.8/52 {USD/household/week}
Average Fodder Planting Cost per Household = 1.7/52 {USD/household/week}
Avg exotic bull cost = 1
Avg inflation rate = 0.0544/52 {1/week}
Breeding Stock Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Calve Male to Female Ratio = 0.5 {unitless}
Calves Fractional Death Rate = (0.023/52)*Resource Availability Effect on Cattle Mortality {1/week}
Calves per parturition = 1 {cattle/calving}
Cattle disease prevalence rate = 1 {unitless}
Consumption Rate Per Cattle = Resource per Cattle*Effect of cattle population movement on forage harvest efficiency {kg of feed/cattle/week}
Cost of Artificial Insemination Service Over Time = Number of Artificial Insemination Services per week*Artificial Insemination Cost per Service*Actual AI Used {USD/week}
Desired Artificial Insemination Attempt per Cow = 1 {AI/cattle}
Desired Percentage of Breeding Cows Serviced With AI = 0 {unitless}
Do nothing = 1 {unitless}
Do nothing 1 = 1 {unitless}
Effect of cattle population movement on forage harvest efficiency = GRAPH(Normalized cattle population movement {1/week})
(0.000, 0.000), (1.000, 0.421052631579), (1.500, 0.710526315789), (2.000, 0.808270676692)
Effect of Farmers Per Animal Health Assistant on Mortality = GRAPH(farmers per animal health assit {unitless})
(0.0, 0.000), (10.0, 0.132352941176), (20.0, 0.352941176471), (30.0, 0.595588235294), (40.0, 1.00735294118), (50.0, 1.30882352941), (60.0, 1.54411764706), (70.0, 1.750), (80.0, 1.875), (90.0, 1.93382352941), (100.0, 1.93382352941)
Effect of milk production increase due to policy on VC channels = SMTH1(Normalized milk production based on baseline results,5) {unitless}
Effect of profit on production = MIN(((Smoothed producers profit/INIT(Smoothed producers profit))^0.5),1) {unitless}
Ex bull FR success rate = 1
Exotic bull success rate = Use of exotic bull*Ex bull FR success rate

Expected natural breeding rate = ((Milk Producing Cows+Dry cows)*Number of births per cattle per year*Calves per parturition)/52 {cattle/week}
farmers per animal health assistant = 5 {Farmers/animal heath assistant}
Fertilization Success Rate = GRAPH(Male to Female Ratio {unitless})
(0, 0.000), (0.005, 0.507518796992), (0.01, 0.872180451128), (0.015, 0.973684210526), (0.02, 1.000)
Fractional Abortion Rate = (0.01/52)*Resource Availability Effect on Cattle Mortality {unitless}
Gestation Period = 39 {week}
Hub introduction time = IF TIME <156 THEN 0 ELSE 1 {unitless}
Improved to local breed ratio = Mixed breed dairy cattle. Total Mixed Breed Cattle Population/Total Cattle Population {unitless}
Lactation period = 36 {week}
Lagged rainfall = DELAY(Rainfall 1, 12) {mm/week}
Male to Female Ratio = MAX((Adult Male/(Dry cows+Milk Producing Cows)),0.01) {unitless}
Market hub = 0 {unitless}
Milk Price per Litre at Individual Consumers Market = 0.48*Price sensitivity {USD/litre}
Milk Price per Litre at Milk Collection Center = 0.4*Price sensitivity {USD/litre}
Milk Price per Litre at Traders Market = 0.4*Price sensitivity {USD/litre}
Minimum Wage per Hour in Tanzania = 0.26 {USD/hr}
Normalized cattle population movement = Total Cattle Population/INIT(Total Cattle Population) {unitless}
Normalized milk production based on baseline results = IF Produced Milk<18130 THEN (1) ELSE (Baseline milk production/Produced Milk) {unitless}
Number of Artificial Insemination Services per week = Number of Cattle Fertilized with Artificial Insemination*Desired Artificial Insemination Attempt per Cow {AI/week}
Number of births per cattle per year = 0.67*Resource Availability Effect on Cattle Fertility {calving/cattle/year}
Number of Cattle Fertilized with Artificial Insemination = Proportion of AI use*Expected natural breeding rate {cattle/week}
Number of Households in Study Area = 106 {household}
Number of Households Planting Fodder = 2 {household}
Number of Households Purchasing Fodder = 3 {household}
Number of Households Using Animal Health Service = 104 {household}
Number of Households Using Crop Residues = 32 {household}
Number of Households Using Feed Concentrate = 7 {household}
Number of Households Using Other Farmers Bull = 99 {households}
Number of Labor Hours Spent per Household on Cattle per Week = 100.65 {hrs/household/week}
Policy Setting = 1 {unitless}
Policy Setting 2 = 1 {unitless}
Policy Switch 2 = (IF(Do nothing 1=1)THEN(0)ELSE(Policy Setting 2*Market hub))*Hub introduction time {unitless}
Policy Switch1 = IF(Do nothing=1)THEN(0)ELSE(Policy Setting*AI) {unitless}
Preadult Female Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Preadult Female Fractional Sales Rate = 0.01/52 {1/week}
Preadult Male Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Preadult Male Fractional sales rate = 0.9/52 {1/week}
Price sensitivity = 1 {unitless}
Proportion of AI use = Desired Percentage of Breeding Cows Serviced With AI*Policy Switch1*AI introduction time {unitless}
Rainfall Seasonality = IF(Seasonality1>0)THEN(1)ELSE(0) {unitless}
Resource Availability Effect on Cattle Fertility = MIN(((Smoothed Resource Available per Cattle/INIT(Smoothed Resource Available per Cattle))^1.4),1) {unitless}

Resource Availability Effect on Cattle Mortality = (Smoothed Resource Available per Cattle/INIT(Smoothed Resource Available per Cattle))^-1 {unitless}
Seasonality1 = MAX(SINWAVE(1,52),0)
Smoothed producers profit = DELAY3(Producers Profit Over Time,52) {USD/week}
Smoothed Resource Available per Cattle = SMTH3(Consumption Rate Per Cattle,52) {kg of feed/cattle/week}
Survival rate = 1-Fractional Abortion Rate {unitless}
Time to become Preadult = 52 {week}
Time to Mature = 130 {week}
Total Adult Cattle = Adult Male+Dry cows {cattle}
Total Animal Health Service Cost = Number of Households Using Animal Health Service*Average Expenditure per Household on Animal Health {USD/week}
Total Bull Service Cost = (Number of Households Using Other Farmers Bull*Average Cost of Using Other Farmers Bull per Service)/52 {USD/week}
Total Cattle Population = (Total Young Cattle+Total Adult Cattle+Milk Producing Cows+Mixed breed dairy cattle.Total Mixed Breed Cattle Population)*Actual movement {cattle}
Total Cost of Using Crop Residues = Number of Households Using Crop Residues*Average Cost of Using Crop Residues per Household {USD/week}
Total Feed Concentrate Cost = Number of Households Using Feed Concentrate*Average Cost of Feed Concentrate per Household {USD/week}
Total Fodder Planting Cost = Number of Households Planting Fodder*Average Fodder Planting Cost per Household {USD/week}
Total Labor Cost = Total Number of Hrs Spent on Livestock Activities*Minimum Wage per Hour in Tanzania*0 {USD/week}
Total Number of Hrs Spent on Livestock Activities = Number of Households in Study Area*Number of Labor Hours Spent per Household on Cattle per Week {hrs/week}
Total Purchased Fodder Cost = Number of Households Purchasing Fodder*Average Cost of Purchasing Fodder per Household {USD/week}
Total Weekly Operational Cost = Cost of Artificial Insemination Service Over Time+Total Labor Cost+Total Animal Health Service Cost+Total Fodder Planting Cost+Total Cost of Using Crop Residues+Total Feed Concentrate Cost+Total Purchased Fodder Cost+Total Bull Service Cost {USD/week}
Total Young Cattle = Calves+Preadult Male+Preadult Female {cattle}
Transhuman movement = IF Lagged rainfall <12 THEN (0.77) ELSE (1) {unitless}
Use of exotic bull = Avg exotic bull cost
Weighted milk yield per cow = (Improved to local breed ratio*Improved Cow Yield per Week)+((1-Improved to local breed ratio)*Local Cow Milk yield per cow per week) {litre/cattle/week}

Mixed breed dairy cattle:

Adult Male(t) = Adult Male(t - dt) + (Becoming Adult Male - Adult Male Death Rate - Adult Male Slaughter Rate) * dt
INIT Adult Male = 0 {cattle}
INFLOWS:
Becoming Adult Male = Preadult Male/Time to Mature {cattle/week}
OUTFLOWS:
Adult Male Death Rate = Adult Male*Adults Fractional Death Rate {cattle/week}
Adult Male Slaughter Rate = Adult Male*Adult Male Sale Rate {cattle/week}
Calves(t) = Calves(t - dt) + (Mixed Breed Calving + AI Calving - Calves Death Rate - Becoming Preadult Male - Becoming Preadult Female) * dt
INIT Calves = 0 {cattle}

INFLOWS:

Mixed Breed Calving = DELAY3((Mixed breed cattle breeding rate*Survival rate), Gestation Period) {cattle/week}

AI Calving = DELAY3((AI breeding rate*Survival rate), Gestation Period) {cattle/week}

OUTFLOWS:

Calves Death Rate = Calves*Calves Fractional Death Rate {cattle/week}

Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio 1 {cattle/week}

Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio 1 {cattle/week}

Dry cows(t) = Dry cows(t - dt) + (Becoming Breeding Female + Drying - Breeding Stock Slaughter Rate - Breeding Stock Death Rate - Becoming Milk Producers) * dt

INIT Dry cows = 0 {Cattle}

INFLOWS:

Becoming Breeding Female = Preadult Female/Time to Mature {cattle/week}

Drying = Milk Producing Cows/Lactation period {cattle/week}

OUTFLOWS:

Breeding Stock Slaughter Rate = Dry cows/Average Breeding Period {cattle/week}

Breeding Stock Death Rate = Dry cows*Breeding Stock Fractional Death Rate {cattle/week}

Becoming Milk Producers = Mixed Breed Calving {cattle/week}

Gestation Delay(t) = Gestation Delay(t - dt) + (Mixed breed cattle breeding rate + AI breeding rate - Mixed Breed Calving - Still born rate - AI Calving) * dt

INIT Gestation Delay = 0 {cattle}

INFLOWS:

Mixed breed cattle breeding rate = ((Dry cows+Milk Producing Cows)*Calving rate*Calves per parturition*Productive portion of breeding stock*Fertilization Success Rate)/52 {cattle/week}

AI breeding rate = Beef & Dairy.Artificial insemination success breeding rate*Beef & Dairy. Actual effect of profit on production {cattle/week}

OUTFLOWS:

Mixed Breed Calving = DELAY3((Mixed breed cattle breeding rate*Survival rate), Gestation Period) {cattle/week}

Still born rate = DELAY3(((Mixed breed cattle breeding rate+AI breeding rate)*Fractional Abortion Rate), Gestation Period) {cattle/week}

AI Calving = DELAY3((AI breeding rate*Survival rate), Gestation Period) {cattle/week}

Milk Producing Cows(t) = Milk Producing Cows(t - dt) + (Becoming Milk Producers - Drying - Milk Producing Cows Death Rate) * dt

INIT Milk Producing Cows = 0 {cattle}

INFLOWS:

Becoming Milk Producers = Mixed Breed Calving {cattle/week}

OUTFLOWS:

Drying = Milk Producing Cows/Lactation period {cattle/week}

Milk Producing Cows Death Rate = Milk Producing Cows*Breeding Stock Fractional Death Rate {cattle/week}

Preadult Female(t) = Preadult Female(t - dt) + (Becoming Preadult Female - Becoming Breeding Female - Preadult Female Death Rate - Preadult Female Sales Rate) * dt

INIT Preadult Female = 0 {cattle}

INFLOWS:
Becoming Preadult Female = (Calves/Time to become Preadult)*Male to Female Ratio 1 {cattle/week}
OUTFLOWS:
Becoming Breeding Female = Preadult Female/Time to Mature {cattle/week}
Preadult Female Death Rate = Preadult Female*Preadult Female Fractional Death Rate {cattle/week}
Preadult Female Sales Rate = Preadult Female*Preadult Female Fractional Sales Rate {cattle/week}

Preadult Male(t) = Preadult Male(t - dt) + (Becoming Preadult Male - preadult Male Sales Rate - Preadult Male Death Rate - Becoming Adult Male) * dt
INIT Preadult Male = 0 {cattle}
INFLOWS:
Becoming Preadult Male = (Calves/Time to become Preadult)*Male to Female Ratio 1 {cattle/week}
OUTFLOWS:
preadult Male Sales Rate = Preadult Male*Preadult Male Fractional sales rate {cattle/week}
Preadult Male Death Rate = Preadult Male*Preadult Male Fractional Death Rate {cattle/week}
Becoming Adult Male = Preadult Male/Time to Mature {cattle/week}

Adult Male Sale Rate = 0.7/52 {1/week}
Adults Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Average Breeding Period = 416 {week}
Breeding Stock Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Calves Fractional Death Rate = (0.023/52)*Resource Availability Effect on Cattle Mortality {1/week}
Calves per parturition = 1 {cattle/calving}
Calving rate = 1 {calving/cattle/year}
Fertilization Success Rate = GRAPH(Male to Female Ratio {unitless})
(0, 0.000), (0.005, 0.507518796992), (0.01, 0.872180451128), (0.015, 0.973684210526), (0.02, 1.000)
Fractional Abortion Rate = (0.01/52)*Resource Availability Effect on Cattle Mortality {unitless}
Gestation Period = 39 {week}
Lactation period = 44 {week}
Male to Female Ratio = MIN((Adult Male/Dry cows),0.01) {unitless}
Male to Female Ratio 1 = 0.5 {unitless}
Preadult Female Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Preadult Female Fractional Sales Rate = 0.01/52 {1/week}
Preadult Male Fractional Death Rate = (0.0531/52)*Resource Availability Effect on Cattle Mortality {1/week}
Preadult Male Fractional sales rate = 0.9/52 {1/week}
Productive portion of breeding stock = 1*Resource Availability Effect on Cattle Fertility {unitless}
Resource Availability Effect on Cattle Fertility = MIN(((Beef & Dairy.Smoothed Resource Available per Cattle/INIT(Beef & Dairy.Smoothed Resource Available per Cattle))^1.4),1) {unitless}
Resource Availability Effect on Cattle Mortality = (Beef & Dairy.Smoothed Resource Available per Cattle/INIT(Beef & Dairy.Smoothed Resource Available per Cattle))^-1 {unitless}
Survival rate = 1-Fractional Abortion Rate {unitless}
Time to become Preadult = 52 {week}
Time to Mature = 130 {week}
Total Mixed Breed Cattle Population = Calves+Preadult Male+Adult Male+Dry cows+Preadult Female+Milk Producing Cows {cattle}

Appendix C: Goat module equations

Accumulated Investment Cost(t) = Accumulated Investment Cost(t - dt) + (Investing - Paying Debts) * dt

INIT Accumulated Investment Cost = 2940*75 {Mt}

INFLOWS:

Investing = ((Vet Service Costs*Total Number of Goats)/52)+(Increasing Breeding Stock*Avg Quality Breeding Goat Price) {Mt/week}

OUTFLOWS:

Paying Debts = (Aggregators Purchase Rate+Selling to Local Market+Aggregators Purchase Rate of Adult Male Goats)*Vet Service Costs

Accumulated Vet Service Time(t) = Accumulated Vet Service Time(t - dt) + (Providing Services - Service Depletion) * dt

INIT Accumulated Vet Service Time = 0

INFLOWS:

Providing Services = Vet Services/52

OUTFLOWS:

Service Depletion = DELAY(Providing Services,52,0)

Adult Male(t) = Adult Male(t - dt) + (Maturation Rate - Breeding Stock Increase Rate - Male Aging - Mature Deaths - Aggregators Purchase Rate of Adult Male Goats) * dt

INIT Adult Male = 229 {goat}

INFLOWS:

Maturation Rate = ((Young Stock/Maturation Time)*Female to Male Ratio) {goat/week}

OUTFLOWS:

Breeding Stock Increase Rate = MIN(Adult Male/Minimum Transfer Time,Indicated Male Goat Transfer) {goat/week}

Male Aging = ((Adult Male*Sale Rate)/52)*Percent of Households Selling Goats {goat/week}

Mature Deaths = (Adult Male*Mature Fractional Death Rate)/52 {goat/week}

Aggregators Purchase Rate of Adult Male Goats = IF(Desired Aggregators Stock 1>Male & Old Breeding Goats For Sale)THEN(MIN((0.8*Adult Male),(Desired Aggregators Stock 1-Male & Old Breeding Goats For Sale))/Time To Aggregate)ELSE(0) {goat/week}

Breeding Stock(t) = Breeding Stock(t - dt) + (Breeding Stock Increase Rate + Goats Kept for Breeding + Increasing Breeding Stock - Breeding Stock Aging - Breeding Stock Deaths) * dt

INIT Breeding Stock = 1450 {goat}

INFLOWS:

Breeding Stock Increase Rate = MIN(Adult Male/Minimum Transfer Time,Indicated Male Goat Transfer) {goatt/week}

Goats Keept for Breeding = (Young Stock/Maturation Time)*Female to Male Ratio {goat/week}

Increasing Breeding Stock = Adding Breeding Goats {goat/week}

OUTFLOWS:

Breeding Stock Aging = ((Breeding Stock/Average Breeding Period))*Percent of Households Selling Goats {goat/week}

Breeding Stock Deaths = (Breeding Stock*Mature Fractional Death Rate)/52 {goat/week}

Gestation Delay(t) = Gestation Delay(t - dt) + (Breeding Rate - Birth Rate - Deaths at Birth) * dt

INIT Gestation Delay = 900 {goat}

INFLOWS:

Breeding Rate = (Breeding Stock*Average Litter Size*Litters per Year*Reproductive Portion)/52 {unit/year}

OUTFLOWS:

Birth Rate = (Gestation Delay/Gestation Period) {unit/year}
Deaths at Birth = (Gestation Delay*At Birth Death Rate)/52 {goat/month}

Local Butchers Accumulated Benefit(t) = Local Butchers Accumulated Benefit(t - dt) + (Selling - Buying - Operation Costs) * dt

INIT Local Butchers Accumulated Benefit = 0
INFLOWS:

Selling = Selling to Local Market*(Avg Selling Price at Local Butchers+Price of by product per Goat) {Mt/week}

OUTFLOWS:

Buying = Selling to Local Market*Avg Goat Price at producer Market {Mt/week}
Operation Costs = Selling to Local Market*Operation Expenses per Goat {Mt/week}

Male & Old Breeding Goats For Sale(t) = Male & Old Breeding Goats For Sale(t - dt) + (Male Aging + Breeding Stock Aging - Aggregators Purchase Rate - Other Consumptions - Selling to Local Market - Old Goats Death Rate) * dt

INIT Male & Old Breeding Goats For Sale = 461 {goat}
INFLOWS:

Male Aging = ((Adult Male*Sale Rate)/52)*Percent of Households Selling Goats {goat/week}
Breeding Stock Aging = ((Breeding Stock/Average Breeding Period))*Percent of Households Selling Goats {goat/week}

OUTFLOWS:

Aggregators Purchase Rate = (MIN(Male & Old Breeding Goats For Sale,Desired Aggregators Stock 1)/Time To Aggregate)+(Desired Aggregators Stock 2/Time To Aggregate) {goat/week}
Other Consumptions = (Male & Old Breeding Goats For Sale*Various Consumption' Rate)/52 {goat/week}
Selling to Local Market = MIN(Male & Old Breeding Goats For Sale/1,Avg Consumption Per Week) {goat/week}
Old Goats Death Rate = (Male & Old Breeding Goats For Sale*Mature Fractional Death Rate)/52 {goat/week}

Producers Accumulated Benefit(t) = Producers Accumulated Benefit(t - dt) + (Aggregator Buying Rate + Buying - Production Cost Rate) * dt

INIT Producers Accumulated Benefit = 0
INFLOWS:

Aggregator Buying Rate = (Aggregators Purchase Rate+Aggregators Purchase Rate of Adult Male Goats)*Avg Goat Price at producer Market {Mt/week}

Buying = Selling to Local Market*Avg Goat Price at producer Market {Mt/week}
OUTFLOWS:

Production Cost Rate = ((Total Number of Goats*(Avg cost per Goat+Vet Service Costs))/52)+(Increasing Breeding Stock*1000) {Mt/week}
Producers Livestock Capital(t) = Producers Livestock Capital(t - dt) + (Liquidizing Farmers Stock of Goats - Depreciation of Farmers Livestock Capital through outflows) * dt
INIT Producers Livestock Capital = ((Breeding Stock + Adult Male+Available Goats For Sale)*Avg Goat Price at producer

Market)+(Young Stock*Avg Young Goat Price at Producer Market) {MZN}

INFLOWS:

Liquidizing Farmers Stock of Goats = (Birth Rate*Avg Young Goat Price at Producer Market)+((Maturation Rate+Goats Kept for Breeding)*Avg Goat Price at producer Market) {Mt/week}

OUTFLOWS:

Depreciation of Farmers Livestock Capital through outflows = ((Old Goats Death Rate+Breeding Stock Deaths+Mature Deaths+Selling to Local Market+Aggregators Purchase Rate+Other Consumptions)*Avg Goat Price at producer Market)+((Young Deaths+Aggregators Purchase Rate of Adult Male Goats+Maturation Rate+Goats Keept for Breeding)*Avg Young Goat Price at Producer Market) {Mt/week}

Young Stock(t) = Young Stock(t - dt) + (Birth Rate - Maturation Rate - Young Deaths - Goats Keept for Breeding) * dt

INIT Young Stock = 800 {goat}

INFLOWS:

Birth Rate = (Gestation Delay/Gestation Period) {unit/year}

OUTFLOWS:

Maturation Rate = ((Young Stock/Maturation Time)*Female to Male Ratio) {goat/week}

Young Deaths = (Young Stock*Young Fractional Death Rate)/52 {goat/week}

Goats Keept for Breeding = (Young Stock/Maturation Time)*Female to Male Ratio {goat/week}

Adding Breeding Goats = IF(TIME=52 AND Policy Switch2 =1)THEN(2000)ELSE(0)

At Birth Death Rate = GRAPH(Accumulated Vet Service Time {1/year})

(0.000, 0.1600), (0.100, 0.157555555556), (0.200, 0.153888888889), (0.300, 0.148592592593), (0.400, 0.132703703704), (0.500, 0.1050), (0.600, 0.0817777777778), (0.700, 0.0675185185185), (0.800, 0.0548888888889), (0.900, 0.0508148148148), (1.000, 0.0500)

Available Goats For Sale = Male & Old Breeding Goats For Sale+Adult Male {goat}

Average Breeding Period = 203 {week}

Average Litter Size = 1.28 {animal/litter}

Avg Consumption Per Week = 3 {goats/week}

Avg cost per Goat = 115 {Mt}

Avg Goat Price at producer Market = 820 {Mt/goat}

Avg Quality Breeding Goat Price = 1000 {Mt}

Avg Selling Price at Local Butchers = 1350 {Mt/goat}

Avg Young Goat Price at Producer Market = 700 {Mt/goat}

Do nothing = 1

Do nothing 1 = 1

Female to Male Ratio = 0.5 {unitless}

Gestation Period = 22 {week}

Improving Veterinary Services = 0

Increasing Breeding Goats = 0

Indicated Male Goat Transfer = Male to Female Ratio*Goats Kept for Breeding {goat/week}

Investment Paid Off = (Producers Accumulated Benefit-Accumulated Investment Cost)*(IF(Investing>0)THEN(1)ELSE(0)) {Mt}

Litters per Year = 1.37 {litter/animal/year}

Livestock Worth Assets Producers = (Young Stock*Avg Young Goat Price at Producer Market)+((Breeding Stock+Adult Male+Male & Old Breeding Goats For Sale)*Avg Goat Price at producer Market)

Male to Female Ratio = 0.1 {unitless}

Maturation Time = 26 {week}

Mature Fractional Death Rate = GRAPH(Accumulated Vet Service Time {1/year})

(0.000, 0.0996296296296), (0.100, 0.0992592592593), (0.200, 0.0977777777778), (0.300, 0.0953703703704), (0.400, 0.0898148148148), (0.500, 0.0724074074074), (0.600, 0.0633333333333), (0.700, 0.057037037037), (0.800, 0.0535185185185), (0.900, 0.0507407407407), (1.000, 0.05)
Minimum Transfer Time = 1 {year}
Offtake rate = (Aggregators+Traders+Retailers)/(Young Stock+Adult Male+Breeding Stock+Male & Old Breeding Goats For Sale)
Operation Expenses per Goat = 300 {Mt/goat}
Percent of Households Selling Goats = 1 {unitless}
Policy Setting = 1
Policy Setting 1 = 1
Policy Switch1 = IF(Do nothing=1)THEN(0)ELSE(Policy Setting*Improving Veterinary Services)
Policy Switch2 = IF(Do nothing 1=1)THEN(0)ELSE(Policy Setting 1*Increasing Breeding Goats)
Price of by product per Goat = 100 {Mt/goat}
Producers Accumulated Profit & Livestock asset = Livestock Worth Assets Producers+Investment Paid Off
Return of Investment Local Butchers = Local Butchers Accumulated Benefit-Baseline Local Butchers Accumulated Profit {Mt}
Return of Investment Producers = Producers Accumulated Benefit-Baseline Producers Accumulated Profit {Mt}
Return of Investment Producers Worth Livestock Assets = Livestock Worth Assets Producers-Baseline Livestock Worth Assets Producers {Mt}
Reproductive Portion = 0.9 {Unitless}
Sale Rate = 1 {year}
Time To Aggregate = 2 {week}
Total Number of Goats = Breeding Stock+Adult Male+Young Stock+Male & Old Breeding Goats For Sale
Various Consumption' Rate = 0.25 {1/year}
Vet Service Costs = IF(Vet Services>0)THEN(75)ELSE(0)
Vet Services = IF(Policy Switch1>0)THEN(1)ELSE(0)
Young Fractional Death Rate = GRAPH(Accumulated Vet Service Time {1/year})
(0.000, 0.2800), (0.111111111111, 0.276666666667), (0.222222222222, 0.2720), (0.333333333333, 0.258666666667), (0.444444444444, 0.2200), (0.555555555556, 0.177333333333), (0.666666666667, 0.144666666667), (0.777777777778, 0.1180), (0.888888888889, 0.107333333333), (1.000, 0.1000)

Appendix D: Sheep module equations

Breeding Ewes(t) = Breeding Ewes(t - dt) + (Breeding Stock Increase Rate - Breeding Stock Slaughter Rate) * dt

INIT Breeding Ewes = Annual Customer Demand {cattle}

INFLOWS:

Breeding Stock Increase Rate = Maximum Breeding Stock Increase Rate*Indicated Breeding Stock Increase Rate {sheep/week}

OUTFLOWS:

Breeding Stock Slaughter Rate = Breeding Ewes/Avg Breeding Period {sheep/week}

Breeding Stock Adjustment(t) = Breeding Stock Adjustment(t - dt) + (Change in breeding stock adjustment) * dt

INIT Breeding Stock Adjustment = Breeding Stock Gap {pig/week}

INFLOWS:

Change in breeding stock adjustment = (Breeding Stock Gap-Breeding Stock Adjustment)/Gap Adjustment Time {pig/week/week}

Female Lamb(t) = Female Lamb(t - dt) + (Female Weaning - Breeding Stock Increase Rate - Female Lamb Slaughter ing) * dt

INIT Female Lamb = (Customer Order*Feeding Time)/2 {sheep}

INFLOWS:

Female Weaning = (Weaners/Time to Mature)*0.5 {sheep/week}

OUTFLOWS:

Breeding Stock Increase Rate = Maximum Breeding Stock Increase Rate*Indicated Breeding Stock Increase Rate {sheep/week}

Female Lamb Slaughter ing = (Female Lamb/Feeding Time)-Breeding Stock Increase Rate {sheep/week}

Gestation(t) = Gestation(t - dt) + (Breeding Rate - Birth Rate) * dt

INIT Gestation = (Customer Order*Gestation Period) {sheep}

INFLOWS:

Breeding Rate = (Breeding Ewes*Litters per Year*Avg litter size)/52 {cattle/year}

OUTFLOWS:

Birth Rate = Gestation/Gestation Period {sheep/week}

Male lamb(t) = Male lamb(t - dt) + (Male Weaning - Male Lamb Slaughtering) * dt

INIT Male lamb = (Customer Order*Feeding Time)/2 {sheep/week}

INFLOWS:

Male Weaning = (Weaners/Time to Mature)*0.5 {sheep/week}

OUTFLOWS:

Male Lamb Slaughtering = Male lamb/Feeding Time {sheep/week}

Weaners(t) = Weaners(t - dt) + (Birth Rate - Female Weaning - Male Weaning) * dt

INIT Weaners = (Customer Order*Time to Mature) {sheep}

INFLOWS:

Birth Rate = Gestation/Gestation Period {sheep/week}

OUTFLOWS:

Female Weaning = (Weaners/Time to Mature)*0.5 {sheep/week}

Male Weaning = (Weaners/Time to Mature)*0.5 {sheep/week}

Avg Breeding Period = 130 {week}
Avg litter size = 1 {animal/litter}
Breeding Ewes Adjustment Time = 1 {week}
Breeding Stock Gap = ((Desired Breeding Stock-Breeding Ewes)/Breeding Ewes Adjustment Time)+Perceived Breeding Stock Slaughter Rate {sheep/week}
Breeding Stock Perception time = 52 {week}
Desired Breeding Stock = Production Capacity*Capacity Utilization {sheep}
Feeding Time = 39 {week}
Gap Adjustment Time = 26 {week}
Gestation Period = 22 {week}
Indicated Breeding Stock Increase Rate = MAX(0,(Breeding Stock Adjustment/Female Lamb)) {1/week}
Litters per Year = 1 {litter/animal/year}
Maximum Breeding Stock Increase Rate = DELAY(Female Lamb,Transfer Time) {sheep}
Perceived Breeding Stock Slaughter Rate = SMTH1(Breeding Stock Slaughter Rate,Breeding Stock Perception time) {sheep/week}
Percentage Leg Chump = 0.326 {1/week}
Production Capacity = Capacity Stock*Capital Productivity {sheep}
Time to Mature = 52 {week}
Transfer Time = 1 {week}

Appendix E: Pigs module equations

Boar(t) = Boar(t - dt) + (Maturing + Boar restocking - Boar selling - Boar dying) * dt
INIT Boar = 61 {pig}
INFLOWS:
Maturing = Young adult male/Time to mature {pig/week}
Boar restocking = 0.1*Sow restocking {pig/week}
OUTFLOWS:
Boar selling = (Boar/Boar service time)+(Boar*Panic sale ASF) {pig/week}
Boar dying = Boar*Boar mortality rate {pig/week}

Farmer capacity(t) = Farmer capacity(t - dt) + (Change in capacity) * dt
INIT Farmer capacity = 2000 {pig}
INFLOWS:
Change in capacity = (Desired capacity-Farmer capacity)/Adjustment time {pig/week}

Feedlot(t) = Feedlot(t - dt) + (Male weaner selling + Female weaner selling - Selling growers for slaughter) * dt
INIT Feedlot = 276 {pig}
INFLOWS:
Male weaner selling = Male weaning*Male weaner sales rate {pig/week}
Female weaner selling = Female weaning*Female weaner sales rate {pig/week}
OUTFLOWS:
Selling growers for slaughter = (DELAY((Male weaner selling+Female weaner selling), Time in feedlot)*(IF Feedlot<15 THEN 0 ELSE 1))+(Feedlot*Panic sale ASF) {pig/week}

Gestation(t) = Gestation(t - dt) + (Breeding - Farrowing - Aborting) * dt
INIT Gestation = 1520 {pig}
INFLOWS:
Breeding = (Sow*Conception rate*Litter size per farrowing*Number of farrowing per sow per year)/52 {pig/week}
OUTFLOWS:
Farrowing = (DELAY3(Breeding,Gestation period)-Aborting)*Effect of ASF on farrowing {pig/week}
Aborting = DELAY3((Breeding*Abortion rate),Gestation period) {pig/week}

Gilt(t) = Gilt(t - dt) + (Becoming gilt - Becoming sow - Gilt dying - Selling guilt) * dt
INIT Gilt = 198 {pig}
INFLOWS:
Becoming gilt = DELAY((Female weaning*Percent female weaner allocated to breeding), Time to become gilt) {pig/week}
OUTFLOWS:
Becoming sow = (DELAY(Becoming gilt,Time to become sow)*(IF Gilt<2 THEN 0 ELSE 1))-Gilt dying-Selling guilt {pig/week}
Gilt dying = DELAY((Becoming gilt*Gilt mortality rate),Time to become sow)*(IF Gilt<2 THEN 0 ELSE 1) {pig/week}
Selling guilt = DELAY((Becoming gilt*Guilt sales rate),Time to become sow)+(Gilt*Panic sale ASF) {pig/week}

Market inventory producers(t) = Market inventory producers(t - dt) + (Supplying pigs to the market) * dt
INIT Market inventory producers = Boar selling+Sow selling+Selling growers+Selling growers for slaughter+Young adult panic selling {pig}

INFLOWS:

Supplying pigs to the market = Sow selling+Boar selling+Selling growers+Selling growers for slaughter+Young adult panic selling {pig/week}

On farm fatteners(t) = On farm fatteners(t - dt) + (On farm fattening - Growers dying - Selling growers) * dt

INIT On farm fatteners = 199 {pig}

INFLOWS:

On farm fattening = Male weaning*Percent weaner allocated for on farm fattening {pig/week}

OUTFLOWS:

Growers dying = DELAY((On farm fattening*Growers mortality rate),Fattening time) {pig/week}

Selling growers = (DELAY(On farm fattening,Fattening time)*(IF On farm fatteners<1 THEN 0 ELSE 1))+(On farm fatteners*Panic sale ASF) {pig/week}

Piglet(t) = Piglet(t - dt) + (Farrowing - Male weaning - Female weaning - Piglet dying - Piglet panic selling) * dt

INIT Piglet = 274 {pig}

INFLOWS:

Farrowing = (DELAY3(Breeding,Gestation period)-Aborting)*Effect of ASF on farrowing {pig/week}

OUTFLOWS:

Male weaning = (Piglet/Time to grow to weaner)*Sex ratio {pig/week}

Female weaning = (Piglet/Time to grow to weaner)*Sex ratio {pig/week}

Piglet dying = Farrowing*Piglet mortality rate {pig/week}

Piglet panic selling = Piglet*Panic sale ASF

Sow(t) = Sow(t - dt) + (Becoming sow + Sow restocking - Sow selling - Sow dying) * dt

INIT Sow = 95 {pig}

INFLOWS:

Becoming sow = (DELAY(Becoming gilt,Time to become sow)*(IF Gilt<2 THEN 0 ELSE 1))-Gilt dying-Selling guilt {pig/week}

Sow restocking = Sow restocking rate {pig/week}

OUTFLOWS:

Sow selling = (Sow/Average breeding period)+(Sow*Panic sale ASF) {pig/week}

Sow dying = Sow*Sow mortality rate {pig/week}

Young adult male(t) = Young adult male(t - dt) + (Male weaner allocating for breeding - Maturing - Young adult panic selling - Young adult dying) * dt

INIT Young adult male = 47 {pig}

INFLOWS:

Male weaner allocating for breeding = Male weaning*Percent male weaner allocated for breeding {pig/week}

OUTFLOWS:

Maturing = Young adult male/Time to mature {pig/week}

Young adult panic selling = Young adult male*Panic sale ASF

Young adult dying = Young adult male*Growers mortality rate {pig/week}

Female weaner death rate = Female weaning*Female weaner mortality rate {pig/week}

Male weaner dying = Male weaning*Male weaner mortality rate {pig/week}

Abortion rate = 0.05 {1/week}

Adjustment time = 52 {week}

Average breeding period = 104 {week}

Boar mortality rate = (0.06/52)+Effect of ASF on death rate and home slaughter {1/week}
Boar pig unit = 1.2 {pig unit/pig}
Boar service time = 104 {week}
Boar to sow ratio = Boar/Sow {unitless}
Conception rate = GRAPH(Boar to sow ratio {unitless})
(0, 0.000), (0.01, 0.043), (0.02, 0.099), (0.03, 0.186), (0.04, 0.336), (0.05, 0.510), (0.06, 0.711), (0.07, 0.838), (0.08, 0.881), (0.09, 0.889), (0.1, 0.900)
Desired capacity = Farmer capacity*Effect of gross margin on capacity {pig}
Effect of inventory on value chain actors price = (Perceived Inventory/INIT(Perceived Inventory))^-0.02
Effect of inventory on producers price = (Perceived Inventory/INIT(Perceived Inventory))^-0.04
Effect of space on breeding decision = GRAPH(Space)
(0.000, 0.800), (0.250, 0.750), (0.440, 0.600), (0.750, 0.250), (1.000, 0.000)
Effect of space on guilt sales rate = GRAPH(Space)
(0.000, 0.000), (0.250, 0.031746031746), (0.440, 0.100), (0.750, 0.406349206349), (1.000, 0.549206349206)
Fattening time = IF Panic sale ASF>0 THEN 1 ELSE 26 {week}
Female weaner mortality rate = 0.11+Effect of ASF on death rate and home slaughter {1/week}
Female weaner sales rate = 1-Percent female weaner allocated to breeding-Female weaner mortality rate {1/week}
Gestation period = 15.5 {week}
Gilt & finisher pig unit = 0.6 {Pig unit/pig}
Gilt mortality rate = (0.11)+Effect of ASF on death rate and home slaughter {1/week}
Growers mortality rate = 0.02+Effect of ASF on death rate and home slaughter {1/week}
Guilt sales rate = MAX(Effect of space on guilt sales rate,Panic sale ASF) {1/week}
Litter size per farrowing = 8 {pig/farrowing}
Male weaner mortality rate = 0.11+Effect of ASF on death rate and home slaughter {1/week}
Male weaner sales rate = 1-Percent male weaner allocated for breeding-Percent weaner allocated for on farm fattening-Male weaner mortality rate {1/week}
Number of farrowing per sow per year = 2 {farrowing/pig/year}
Perceived Inventory = SMTH3(Market inventory producers, 8)
Percent female weaner allocated to breeding = Effect of space on breeding decision*Breeding decision during ASF {1/week}
Percent male weaner allocated for breeding = 0.1*Breeding decision during ASF {1/week}
Percent weaner allocated for on farm fattening = 0.1*Breeding decision during ASF {1/week}
Peri Urban farmer capacity = Effect of gross margin on capacity*2000 {pig}
Piglet mortality rate = 0.21+Effect of ASF on death rate and home slaughter {1/week}
Piglet pig unit = 0.3 {pig unit/pig}
Sex ratio = 0.5 {unitless}
Sow mortality rate = (0.11/52)+Effect of ASF on death rate and home slaughter {1/week}
Sow pig unit = 1 {pig unit/pig}
Space = Total pig population/Peri Urban farmer capacity {unitless}
Time in feedlot = 26 {week}
Time to become gilt = 16 {week}
Time to become sow = 8 {week}
Time to grow to weaner = 8 {week}
Time to mature = 24 {week}
Total pig population = Sow+On farm fatteners+Gilt+Piglet+Boar+Young adult male {pig}
Total pig unit equivalent in producers stocks = (Piglet*Piglet pig unit)+((Gilt+On farm fatteners+Young adult male)*Gilt & finisher pig unit)+(Sow*Sow pig unit)+(Boar*Boar pig unit) {pig unit}

Appendix F: Post farm-gate value chains module equations

Butchers cumulative annual profit(t) = Butchers cumulative annual profit(t - dt) + (Butchers profit over time - Butchers profit) * dt

INIT Butchers cumulative annual profit = 0 {USh}

INFLOWS:

Butchers profit over time = Butchers gross margin over time {USh/week}

OUTFLOWS:

Butchers profit = PULSE(Butchers cumulative annual profit,52,52) {USh/week}

Cumulative profit per pig unit(t) = Cumulative profit per pig unit(t - dt) + (Profit per pig unit per week - Pig unit profit) * dt

INIT Cumulative profit per pig unit = 96100 {UGS/pig unit}

INFLOWS:

Profit per pig unit per week = Profit per pig unit {UGS/pig unit/week}

OUTFLOWS:

Pig unit profit = PULSE(Cumulative profit per pig unit,52,52)

Local butchers pork inventory(t) = Local butchers pork inventory(t - dt) + (Local butchers processing pig to pork - Local butchers selling pork to local consumers) * dt

INIT Local butchers pork inventory = Local butchers processing pig to pork {kg of pork}

INFLOWS:

Local butchers processing pig to pork = (Producers selling pigs to local butchers+Traders allocating pigs for own butchering+Collectors selling to local butchers+Collectors allocating pigs for butchering+ Wholesalers selling to local butchers+Wholesalers allocating pigs for butchering+ Traders selling to local butchers)*Pig to carcass conversion ratio*Average carcass weight {kg of pork/week}

OUTFLOWS:

Local butchers selling pork to local consumers = Local butchers pork inventory*Percentage allocated to local consumers {kg of pork/week}

Market inventory producers(t) = Market inventory producers(t - dt) + (Supplying pigs to the market - Producers selling pigs to local butchers - Producers selling to consumers - Producers selling to wholesalers - Producers selling to collectors - Producers selling to traders) * dt

INIT Market inventory producers = Boar selling+Sow selling+Selling growers+Selling growers for slaughter+Young adult panic selling {pig}

INFLOWS:

Supplying pigs to the market = Sow selling+Boar selling+Selling growers+Selling growers for slaughter+Young adult panic selling {pig/week}

OUTFLOWS:

Producers selling pigs to local butchers = Market inventory producers*Percentage pig sold to local butchers {pig/week}

Producers selling to consumers = Market inventory producers*Percentage pig sold directly to consumers {pig/week}

Producers selling to wholesalers = Market inventory producers*Percentage pig sold to wholesalers {pig/week}

Producers selling to collectors = Market inventory producers*Percentage pig sold to collectors {pig/week}

Producers selling to traders = Market inventory producers*Percentage pig sold to traders {pig/week}

Pig collectors(t) = Pig collectors(t - dt) + (Producers selling to collectors - Collectors allocating pigs for butchering - Collectors selling to traders - Collectors selling to local butchers - Collectors selling to wholesalers) * dt

INIT Pig collectors = Market inventory producers*Percentage pig sold to collectors {pig}

INFLOWS:

Producers selling to collectors = Market inventory producers*Percentage pig sold to collectors {pig/week}

OUTFLOWS:

Collectors allocating pigs for butchering = Pig collectors*Percentage collectors pig allocate for own butchering {pig/week}

Collectors selling to traders = Pig collectors*Percentage collectors pig sold to traders {pig/week}

Collectors selling to local butchers = Pig collectors*Percentage collectors pig sold to local butchers {pig/week}

Collectors selling to wholesalers = Pig collectors*Percentage collectors pig sold to wholesalers {pig/week}

Pig collectors cumulative annual profit(t) = Pig collectors cumulative annual profit(t - dt) + (Pig collectors profit over time - Pig collectors profit) * dt

INIT Pig collectors cumulative annual profit = 0 {USh}

INFLOWS:

Pig collectors profit over time = Pig collectors gross margin over time {USh/week}

OUTFLOWS:

Pig collectors profit = PULSE(Pig collectors cumulative annual profit,52,52) {USh/week}

Producers cumulative annual profit(t) = Producers cumulative annual profit(t - dt) + (Producers profit over time - Prodcuers profit) * dt

INIT Producers cumulative annual profit = 26100*Total pig unit equivalent in producers stocks {USh}

INFLOWS:

Producers profit over time = Producers gross margin over time {USh/week}

OUTFLOWS:

Producers profit = PULSE(Producers cumulative annual profit,52,52) {USh/week}

Producers cumulative gross margin(t) = Producers cumulative gross margin(t - dt) + (Gross margin over time - Cost over time) * dt

INIT Producers cumulative gross margin = 0

INFLOWS:

Gross margin over time = Total pig unit equivalent in producers stocks

OUTFLOWS:

Cost over time = 1

Traders cumulative annual profit(t) = Traders cumulative annual profit(t - dt) + (Traders profit over time - Traders profit) * dt

INIT Traders cumulative annual profit = 0 {USh}

INFLOWS:

Traders profit over time = Traders gross margin over time {USh/week}

OUTFLOWS:

Traders profit = PULSE(Traders cumulative annual profit,52,52)

Traders pig inventory(t) = Traders pig inventory(t - dt) + (Producers selling to traders + Collectors selling to traders - Traders selling to wholesalers - Traders selling to local butchers - Traders allocating pigs for own butchering) * dt

INIT Traders pig inventory = Producers selling to traders+Collectors selling to traders {pig}

INFLOWS:

Producers selling to traders = Market inventory producers*Percentage pig sold to traders {pig/week}

Collectors selling to traders = Pig collectors*Percentage collectors pig sold to traders {pig/week}

OUTFLOWS:

Traders selling to wholesalers = Traders pig inventory*Percentage traders pig sold to wholesalers {pig/week}

Traders selling to local butchers = Traders pig inventory*Percentage traders pig sold to local butchers {pig/week}

Traders allocating pigs for own butchering = Traders pig inventory*Percentage traders pig allocated for own butchering {pig/week}

Wholesalers cumulative annual profit(t) = Wholesalers cumulative annual profit(t - dt) + (Wholesalers profit over time - Wholesalers profit) * dt

INIT Wholesalers cumulative annual profit = 0 {USh}

INFLOWS:

Wholesalers profit over time = Wholesalers gross profit over time {USh/week}

OUTFLOWS:

Wholesalers profit = PULSE(Wholesalers cumulative annual profit,52,52) {USh/week}

wholesalers pig inventory(t) = wholesalers pig inventory(t - dt) + (Producers selling to wholesalers + Collectors selling to wholesalers + Traders selling to wholesalers - Wholesalers allocating pigs for butchering - Wholesalers selling to local butchers - Wholesalers selling pig to slaughter house) * dt

INIT wholesalers pig inventory = Producers selling to wholesalers+Collectors selling to wholesalers+Traders selling to wholesalers {pig}

INFLOWS:

Producers selling to wholesalers = Market inventory producers*Percentage pig sold to wholesalers {pig/week}

Collectors selling to wholesalers = Pig collectors*Percentage collectors pig sold to wholesalers {pig/week}

Traders selling to wholesalers = Traders pig inventory*Percentage traders pig sold to wholesalers {pig/week}

OUTFLOWS:

Wholesalers allocating pigs for butchering = wholesalers pig inventory*Percentage wholesalers pig allocated for own butchering {pig/week}

Wholesalers selling to local butchers = wholesalers pig inventory*Percentage wholsellers pig sold to local butchers {pig/week}

Wholesalers selling pig to slaughterhouse = wholesalers pig inventory*Percentage wholesalers pig allocated o slaughter house {pig/week}

Butchers annual gross margin = PULSE(Butchers cumulative annual profit,52,52) {USh/year}
By products = Local butchers processing pig to pork/Average carcass weight {by product/pig}
Pig collectors annual gross margin = PULSE(Pig collectors cumulative annual profit,52,52) {USh/year}
Producers annual gross margin = PULSE(Producers cumulative annual profit,52,52) {USh/year}
Producers annual profit per pig unit = PULSE(Cumulative profit per pig unit,52,52)
Traders annual gross margin = PULSE(Traders cumulative annual profit,52,52) {USh/year}
Wholesalers annual gross margin = PULSE(Wholesalers cumulative annual profit,52,52) {USh/year}
Aggregated average by product price per pig = 43500 {USh/by product}
ASF control = IF Policy Switch2 > 0 THEN Biosecurity & Market hub ELSE Market hub

Average carcass weight = 55 {kg of pork/carcass}
Average cost per pig unit = 159951/52 {UGS/week}
Average traders processing cost per pig = 5000 {USh/pig}
Avg pig price = 140200*Effect of inventory on producers price*Effect of market hub on producers price {UGS/pig}
Biosecurity & Market hub = IF Policy Switch2 >0 AND Policy Switch1 > 0 THEN 0.25 ELSE 1.9 OR (IF Policy Switch2 > 0 AND Policy Switch1 = 0 THEN (0.95) ELSE (1.9))
Biosecurity practice = 0
Boar pig unit = 1.2 {pig unit/pig}
Boar price = 1.0143*Avg pig price {UGS/pig}
Butchers cost over time = ((Wholesalers selling to local butchers+Wholesalers allocating pigs for butchering)*(Wholesalers average sales price+Butchers operational cost per pig))+((Collectors allocating pigs for butchering+Collectors selling to local butchers)*(Traders average pig sales price+Butchers operational cost per pig))+((Traders allocating pigs for own butchering+Traders selling to local butchers)*(Traders average pig sales price+Butchers operational cost per pig))+((Producers selling pigs to local butchers)*(Avg pig price+Butchers operational cost per pig)) {USh/week}
Butchers gross margin over time = Butchers revenue over time-Butchers cost over time {USh/week}
Butchers operational cost per pig = 50000 {USh/pig}
Butchers revenue over time = (Local butchers selling pork to local consumers*Price per kg of pork)+(By products*Aggregated average by product price per pig) {USh/week}
Collector pig purchase price = Avg pig price {USh/pig}
Converter 1 = SMTH3(Producers cumulative annual profit,26)
Do nothing = 1
Do nothing 1 = 1
Effect of gross margin on capacity = GRAPH(Converter 1 {unitless})
(-1000000, 0.887837837838), (-500000, 0.9071), (0, 1.0000), (500000, 1.0729), (1000000, 1.1000)
Effect of inventory on value chain actors price = (Perceived Inventory/INIT(Perceived Inventory))^-0.02
Effect of inventory on producers price = (Perceived Inventory/INIT(Perceived Inventory))^-0.04
Effect of market hub on producers price = IF Market hub weekly cost > 0 THEN 1.24 ELSE 1
Gilt & finisher pig unit = 0.6 {Pig unit/pig}
Gilt price = 1.0342*Avg pig price {UGS/pig}
Growers and finishers price = 1.1*Avg pig price {UGS/pig}
Hygiene cost per sow = IF Policy Switch2>0 THEN (154583/52) ELSE (0) {USh/pig/week}
Inspection fees per week = (154*12)/52 {USh/week}
Land rent cost per week = (297000*12)/52 {USh/week}
Market hub = IF Policy Switch1 >0 THEN 0.95 ELSE 1.9
Market hub weekly cost = IF Policy Switch1 > 0 THEN (Transport & loading & unloading costs per week+Inspection fees per week+Land rent cost per week) ELSE 0 {USh/week}
Normalized smoothed gross margin = SMTH3(Producers annual gross margin,52, 0)
Perceived Inventory = SMTH3(Market inventory producers, 8)
Percentage allocated to local consumers = 1 {1/week}
Percentage collectors pig allocate for own butchering = 0.06 {1/week}
Percentage collectors pig sold to local butchers = 0.04 {1/week}
Percentage collectors pig sold to traders = 0.2 {1/week}
Percentage collectors pig sold to wholesalers = 0.7 {1/week}
Percentage pig sold directly to consumers = 0.02 {1/week}
Percentage pig sold to collectors = 0.3 {1/week}
Percentage pig sold to local butchers = 0.6 {1/week}
Percentage pig sold to traders = 0.05 {1/week}

Percentage pig sold to wholesalers = 0.03 {1/week}
Percentage traders pig allocated for own butchering = 0.5 {1/week}
Percentage traders pig sold to local butchers = 0.2 {1/week}
Percentage traders pig sold to wholesalers = 0.3 {1/week}
Percentage wholesalers pig allocated for own butchering = 0.05 {1/week}
Percentage wholesalers pig allocated to slaughter house = 0.6 {1/week}
Percentage wholsellers pig sold to local butchers = 0.35 {1/week}
Pig collectors cost over time = Producers selling to collectors*(Collector pig purchase price+Pig collectors operational cost per pig) {USh/week}
Pig collectors gross margin over time = Pig collectors revenue over time-Pig collectors cost over time {USh/week}
Pig collectors operational cost per pig = 650 {USh/pig}
Pig collectors revenue over time = (Collectors selling to wholesalers*Whole sellers average purchase price)+((Collectors allocating pigs for butchering+Collectors selling to traders+Collectors selling to local butchers)*Traders average pig sales price) {pig/week}
Pig market hub = 0
Pig to carcass conversion ratio = 1 {carcass/pig}
Piglet and weaner price = 0.285*Avg pig price {UGS/pig}
Piglet pig unit = 0.3 {pig unit/pig}
Policy Setting = 1
Policy Setting 1 = 1
Policy Switch1 = IF(Do nothing=1)THEN(0)ELSE(Policy Setting*Pig market hub)
Policy Switch2 = IF(Do nothing 1=1)THEN(0)ELSE(Policy Setting 1*Biosecurity practice)
Price per kg of pork = 6500*Effect of inventory on value chain actors price {USh/kg pork}
Producers cost over time = (Total pig unit equivalent in producers stocks*Average cost per pig unit)+(Sow restocking*Sow price)+(Boar restocking*Boar price)+Total policy cost per week {UGS/pig}
Producers gross margin over time = ((Boar selling*Boar price)+(Sow selling*Sow price)+(Selling growers*Growers and finishers price)+(Young adult panic selling*Growers and finishers price)+(Female weaner selling*Piglet and weaner price)+(Male weaner selling*Piglet and weaner price)+(Piglet panic selling*Piglet and weaner price)+(Selling guilt*Gilt price))-Producers cost over time {UGS/pig}
Profit per pig unit = Producers gross margin over time/Total pig unit equivalent in producers stocks {UGS/pig unit}
Sow pig unit = 1 {pig unit/pig}
Sow price = 1.1348*Avg pig price {UGS/pig}
Total hygiene cost per week = Sow*Hygiene cost per sow {USh/week}
Total pig unit equivalent in producers stocks = (Piglet*Piglet pig unit)+((Gilt+On farm fatteners+Young adult male)*Gilt & finisher pig unit)+(Sow*Sow pig unit)+(Boar*Boar pig unit) {pig unit}
Total policy cost per week = Market hub weekly cost+Total hygiene cost per week {USh/week}
Traders average pig purchase price = 160360*Effect of inventory on producers price {USh/pig}
Traders average pig sales price = 189900*Effect of inentory on value chain actors price {USh/pig}
Traders cost over time = (Collectors selling to traders+Producers selling to traders)*(Traders average pig purchase price+Average traders processing cost per pig) {USh/pig}
Traders gross margin over time = Traders revenue over time-Traders cost over time {USh/week}
Traders revenue over time = (Traders allocating pigs for own butchering+Traders selling to local butchers+Traders selling to wholesalers)*Traders average pig sales price {USh/week}
Transport & loading & unloading costs per week = (33000*12)/52 {USh/week}
Whole sellers average purchase price = 189900*Effect of inventory on value chain actors price {USh/pig}
Wholesalers average operational cost per pig = 10000 {USh/pig}
Wholesalers average purchase price = 189900*Effect of inventory on producers price {USh/pig}
Wholesalers average sales price = 291180*Effect of inentory on value chain actors price {USh/pig}

Wholesalers cost over time = (Producers selling to wholesalers+Collectors selling to wholesalers+Traders selling to wholesalers)*(Wholesalers average purchase price+Wholesalers average operational cost per pig) {USh/week}
Wholesalers gross profit over time = Wholesalers revenue over time-Wholesalers cost over time {USh/week}
Wholesalers revenue over time = (Wholesalers selling pig to slaughter house+Wholesalers allocating pigs for butchering+Wholesalers selling to local butchers)*Wholesalers average sales price {USh/week}

Milk:

Milk market hub(t) = Milk market hub(t - dt) + (Milk Sales Rate to Milk market hub - Market hub sales to Processors - Individual buyers) * dt

INIT Milk market hub = 0 {litre}

INFLOWS:

Milk Sales Rate to Milk market hub = Produced Milk*Fractional sales rate to collection centers {litre/week}

OUTFLOWS:

Market hub sales to Processors = Milk market hub*Fractional sales rate to PROC {litre/week}

Individual buyers = Milk market hub*CC sales rate to individual consumers {litre/week}

Milk Production Per Cow(t) = Milk Production Per Cow(t - dt) + (Change in Milk Production) * dt

INIT Milk Production Per Cow = 70 {litre/cattle}

INFLOWS:

Change in Milk Production = Local Cow Milk yield per cow per week-Milk Production Per Cow {litre/cattle/week}

Processors(t) = Processors(t - dt) + (Market hub sales to Processors - Selling to consumers) * dt

INIT Processors = 0 {litre}

INFLOWS:

Market hub sales to Processors = Milk market hub*Fractional sales rate to PROC {litre/week}

OUTFLOWS:

Selling to consumers = Processors/Processing time {litre/week}

Produced Milk(t) = Produced Milk(t - dt) + (Milk Production - Producers Own Consumption Rate - Milk sales rate to individual consumers - Milk sales rate to traders - Milk Sales Rate to Milk market hub - Surplus rate) * dt

INIT Produced Milk = Milk Producing Cows*Local Cow Milk yield per cow per week {litre}

INFLOWS:

Milk Production = (Milk Producing Cows*Local Cow Milk yield per cow per week*Actual movement)+(Stock 1*Improved Cow Yield per Week*Actual movement) {litre/week}

OUTFLOWS:

Producers Own Consumption Rate = Produced Milk*Fractional milk consumption rate by producers {litre/week}

Milk sales rate to individual consumers = Produced Milk*Fractional sales rate to individual consumers {litre/week}

Milk sales rate to traders = Produced Milk*Fraction sales rate to traders {litre/week}

Milk Sales Rate to Milk market hub = Produced Milk*Fractional sales rate to collection centers {litre/week}

Surplus rate = Unsold Surplus {litre/week}

Stock 1(t) = Stock 1(t - dt)

INIT Stock 1 =

CC sales rate to individual consumers = 0.2 {1/week}
Consumption Rate Per Cattle = Resource per Cattle*Effect of cattle population movement on forage harvest efficiency {kg of feed/cattle/week}
Contract farming = IF TIME < 156 THEN 1 ELSE Institution {unitless}
Desired feed = INIT(Total feed provided per cattle) {kg of feed/cattle/week}
Effect of accessing supplementary feed on milk production = (Percentage of farmers accessing supplementary feed/0.57)^0.6 {unitless}
Effect of feed ratio on milk yield = GRAPH(Total feed provided per cattle/Desired feed {unitless})
(0.000, 0.000), (0.200, 0.000), (0.400, 0.036), (0.600, 0.175675675676), (0.800, 0.514), (1.000, 1.000), (1.200, 1.714), (1.400, 1.907), (1.600, 1.957), (1.800, 1.993), (2.000, 2.000)
Effect of milk production increase due to policy on VC channels = SMTH1(Normalized milk production based on baseline results,5) {unitless}
Effect of more produced milk on own consumption = Effect of milk production increase due to policy on VC channels^0.7 {unitless}
Fraction sales rate to traders = 0.15*Contract farming*Effect of milk production increase due to policy on VC channels {1/week}
Fractional milk consumption rate by producers = 0.62*Contract farming*Effect of more produced milk on own consumption {1/week}
Fractional sales rate to collection centers = (1-Fraction sales rate to traders-Fractional sales rate to individual consumers-Fractional milk consumption rate by producers)*Policy Switch 2 {1/week}
Fractional sales rate to individual consumers = 0.23*Contract farming*Effect of milk production increase due to policy on VC channels {1/week}
Fractional sales rate to PROC = 0.8 {1/week}
Improved Cow Yield per Week = Reference Milk Production of Improved Cattle*Effect of feed ratio on milk yield {litre/cattle/week}
Institution = 1 {unitless}
Local Cow Milk yield per cow per week = Reference milk production of Local Cattle*Effect of feed ratio on milk yield {litre/cattle/week}
Percentage of farmers accessing supplementary feed = 0.57 {unitless}
Policy Switch 2 = (IF(Do nothing 1=1)THEN(0)ELSE(Policy Setting 2*Market hub))*Hub introduction time {unitless}
Processing time = 1 {week}
Quantity of milk consumed by producers themselves = 5849*7 {litre of milk/week}
Reference Milk Production of Improved Cattle = 51.2*Effect of accessing supplementary feed on milk production {litre/cattle/week}
Reference milk production of Local Cattle = 13.82*Effect of accessing supplementary feed on milk production {litre/cow/week}
Smoothed feed consumption rate per cattle = SMTH3(Consumption Rate Per Cattle,2) {kg of feed/cattle/week}
Supplementary feed = GRAPH(Smoothed feed consumption rate per cattle {kg of feed/week})
(0.00, 50.00), (20.00, 30.00), (40.00, 10.00), (60.00, 2.00), (80.00, 2.00)
Supplementary feed provided = Supplementary feed*Percentage of farmers accessing supplementary feed {kg of feed/week}
Threshold to sell milk = IF Produced Milk>Quantity of milk consumed by producers themselves THEN (1) ELSE 0
Total feed provided per cattle = Consumption Rate Per Cattle {kg feed/cattle/week}
Unsold Surplus = Produced Milk-Producers Own Consumption Rate-Milk sales rate to individual consumers-Milk sales rate to traders-Milk Sales Rate to Milk market hub {litre/week}
Use of crop residue = Total feed provided per cattle/Desired feed {unitless}

Appendix G: Markets module equations

Industry Demand(t) = Industry Demand(t - dt) + (Change in Industry Demand) * dt

INIT Industry Demand = Reference Industry Demand {carcass/week}

INFLOWS:

Change in Industry Demand = (Indicated Industry Demand-Industry Demand)/Demand Adjustment Delay {carcass/week/week}

Inventory(t) = Inventory(t - dt) + (- Shipment Rate) * dt

INIT Inventory = (Customer Order*Reference Inventory Coverage) {carcass}

OUTFLOWS:

Shipment Rate = Desired Customer Order*Order Fulfillment Ratio {carcass/week}

Producers Expected Price(t) = Producers Expected Price(t - dt) + (Change in Traders' Expected Price) * dt

INIT Producers Expected Price = Initial Price {$/carcass}

INFLOWS:

Change in Traders' Expected Price = ((Indicated Price-Producers Expected Price)/Time to Adjust Price) {$/carcass/week}

Short Run Expected Price(t) = Short Run Expected Price(t - dt) + (Change in Short Run Price) * dt

INIT Short Run Expected Price = Initial Price {$/carcass}

INFLOWS:

Change in Short Run Price = (Price-Short Run Expected Price)/Time to Adjust Short Run Price Expectations {$/carcass/week}

Annual Customer Demand = 52*Customer Order

Capacity Utilization = SMTH1(Indicated Capacity Utilization,Utilization Adjustment Time) {unitless}

Coverage Perception Time = 8.7 {week}

Customer Order = Industry Demand*Other Factors {carcass/week}

Demand = 1+Demand Curve Slope*(Price Difference)/Reference Industry Demand

Demand Adjustment Delay = 4 {week}

Demand Curve Slope = (-Reference Industry Demand*Reference Industry Demand Elasticity)/(Initial Price) {carcass*carcass/($/week)}

Demand Shock = 0

Desired Breeding Stock = Production Capacity*Capacity Utilization {sheep}

Desired Customer Order = Customer Order {carcass/week}

Effect of Cost on Price = 1+Sensitivity of Price to Costs*((Expected Production Costs/Producers Expected Price)-1) {unitless}

Effect of Inventory Coverage on Price = Relative Inventory Coverage^Sensitivity of Price to inventory Coverage {unitless}

Expected Markup = Short Run Expected Price/Expected Variable Cost {unitless}

Expected Production Costs = SMTH1(Unit Costs,Time to Adjust Expected Costs) {$/carcass}

Expected Variable Cost = SMTH1(Unit Variable Cost,Time to Adjust Expected Variable Costs) {$/carcass}

Indicated Capacity Utilization = GRAPH(Expected Markup {unitless})

(0.000, 0.000), (0.250, 0.000), (0.500, 0.000), (0.750, 0.050), (1.000, 0.500), (1.250, 0.680), (1.500, 0.750), (1.750, 0.800), (2.000, 0.840), (2.250, 0.870), (2.500, 0.900), (2.750, 0.930), (3.000, 0.960), (3.250, 0.985), (3.500, 0.995), (3.750, 0.995), (4.000, 1.000), (4.250, 1.000), (4.500, 1.000), (4.750, 1.000), (5.000, 1.000)

Indicated Industry Demand = MIN(Maximum Consumption,Reference Industry Demand)*MAX(0,Demand) {carcass/week}

Indicated Price = MAX(Minimum Price,Price) {$/carcass}

Initial Price = 60 {$/carcass}

Initial Variable Cost Fraction = 0.4 {unitless}
Inventory Coverage = Inventory/Shipment Rate {week}
Long Run Expected Price = SMTH1(Price,Time to Adjust Long Run Price Expectations) {$/carcass}
Maximum Consumption = 1000000 {unit/year}
Maximum Shipment Rate = Inventory/Minimum Order Processing Time {carcass/week}
Minimum Order Processing Time = 1 {week}
Minimum Price = Expected Variable Cost {$/carcass}
Order Fulfillment Ratio = GRAPH(Maximum Shipment Rate/Desired Customer Order {unitless})
(0.000, 0.000), (0.200, 0.200), (0.400, 0.400), (0.600, 0.580), (0.800, 0.730), (1.000, 0.850), (1.200, 0.930), (1.400, 0.970), (1.600, 0.990), (1.800, 1.000), (2.000, 1.000)
Other Factors = 1+(STEP(Demand Shock,200)-STEP(Demand Shock,213))
Perceived Inventory Coverage = SMTH1(Inventory Coverage,Coverage Perception Time) {week}
Price = (Producers Expected Price*Effect of Inventory Coverage on Price*Effect of Cost on Price)*Normalized carcass weight {$/carcass}
Price Difference = Price-Initial Price
Production Capacity = Capacity Stock*Capital Productivity {sheep}
Reference Industry Demand = 520000 {carcass/week}
Reference Industry Demand Elasticity = 0.5 {unitless}
Reference Inventory Coverage = 10.4 {week}
Relative Inventory Coverage = Perceived Inventory Coverage/Reference Inventory Coverage {unitless}
Sensitivity of Price to Costs = 0.25 {unitless}
Sensitivity of Price to inventory Coverage = -0.3 {unitless}
Time to Adjust Expected Costs = 104 {week}
Time to Adjust Expected Variable Costs = 1 {year}
Time to Adjust Long Run Price Expectations = 104 {week}
Time to Adjust Price = 104 {week}
Time to Adjust Short Run Price Expectations = 52 {week}
Unit Costs = Unit Variable Costs+Unit Fixed Costs {$/carcass}
Unit Fixed Costs = Initial Price-Unit Variable Costs {$/carcass}
Unit Variable Cost = (Initial Price)*Initial Variable Cost Fraction {$/unit}
Unit Variable Costs = Initial Variable Cost Fraction*(Initial Price) {$/carcass}
Utilization Adjustment Time = 26 {week}

Appendix H: Preliminary household module equations

Household Finances(t) = Household Finances(t - dt) + (Farm income + Off Farm Income - Household food expenditure - Household clothing expenditure - Household farm expenditure - Household school expenditure - Investment in farm) * dt

INIT Household Finances =

INFLOWS:

Farm income =

Off Farm Income =

OUTFLOWS:

Household food expenditure =

Household clothing expenditure =

Household farm expenditure =

Household school expenditure =

Investment in farm =

Appendix I: Forage module equations

Forage Available(t) = Forage Available(t - dt) + (Forage Growth Rate - Natural Depreciation Rate - Consumption Rate) * dt

INIT Forage Available = 90*Land availability {kg of feed}

INFLOWS:

Forage Growth Rate = (Actual Growth Rate*Land productivity per acre*Land availability) {kg of feed/week}

OUTFLOWS:

Natural Depreciation Rate = Forage Available/Decay Time {kg of feed/week}

Consumption Rate = Total Cattle Population*Consumption Rate Per Cattle {kg of feed/week}

Actual Growth Rate = Normal Growth Rate*Forage Density Effect On Forage Growth {1/week}

Actual Rainfall 1 = IF Policy Switch 1=0 THEN (Rainfall) ELSE (Drought Period*Rainfall) {mm/week}

Consumption Rate Per Cattle = Resource per Cattle*Effect of cattle population movement on forage harvest efficiency {kg of feed/cattle/week}

Decay Time = 104 {week}

Drought Period = IF TIME >104 AND TIME <312 THEN (0.65) ELSE (1) {mm/week}

Effect of cattle population movement on forage harvest efficiency = GRAPH(Normalized cattle population movement {1/week})

(0.000, 0.000), (1.000, 0.421052631579), (1.500, 0.710526315789), (2.000, 0.808270676692)

Feed volume per acre per year = 8000/52 {kg of feed/acre}

Forage Density Effect On Forage Growth = GRAPH(Forage Available/(1500000) {unitless})

(0.000, 0.315), (0.100, 0.725), (0.200, 0.895), (0.300, 0.950), (0.400, 0.925), (0.500, 0.870), (0.600, 0.805), (0.700, 0.670), (0.800, 0.445), (0.900, 0.200), (1.000, 0.005)

Impact of Rainfall on Forage Growth = GRAPH(Actual Rainfall 1 {unitless})

(2.00, 0.010), (6.80, 0.011), (11.60, 0.014), (16.40, 0.023), (21.20, 0.113), (26.00, 0.350), (30.80, 0.734), (35.60, 0.917525773196), (40.40, 0.972508591065), (45.20, 0.993127147766), (50.00, 1.000)

Lag Time = 16 {week}

Lagged Impact of Rainfall on Forage GrowthRate = SMTH1(Impact of Rainfall on Forage Growth,Lag Time,0.25) {unitless}

Land availability = 11152.7 {acre}

Land productivity per acre = (Lagged Impact of Rainfall on Forage GrowthRate*Feed volume per acre per year) {kg of feed/acre}

No Drought = 1 {unitless}

Normal Growth Rate = 1 {1/week}

Policy Setting 1 = 1 {unitless}

Policy Switch 1 = IF(No Drought=1)THEN(0)ELSE(Policy Setting 1*Scenario 3) {unitless}

Resource per Cattle = Forage Available/Total Cattle Population {kg of feed/cattle}

Scenario 3 = 0 {unitless}

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