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Dynamic duo: Exploring mortality rate shock effects in integrated livestock models

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Abstract

This paper explores the synergies between the Dynmod model and the multi-market partial equilibrium model (also known as SectorM), two crucial tools for understanding the dynamics of the livestock sector. Dynmod model excels in capturing intricate herd dynamics over time, representing factors such as offtake rate, mortality rate, parturition rate, age, sex, size, and various demographic attributes. However, Dynmod operates under the assumption of constant prices and economic variables during simulations, limiting its ability to incorporate the dynamic economic conditions that characterize the real-world livestock sector. In contrast, SectorM is proficient in capturing economic factors, considering prices and other variables as endogenous, allowing them to vary over time based on influencing factors. While SectorM excels in economic intricacies, its representation of herd dynamics and demographic factors is comparatively less detailed than Dynmod.

Recognizing the complementary strengths of these models, this research bridges the gap by linking Dynmod and SectorM, using the General Algebraic Modelling System (GAMS) software and focusing on Tanzania's livestock sector as a case study. By doing so, the aim is to harness the detailed herd dynamics of Dynmod alongside the economic adaptability of SectorM, creating a more comprehensive and realistic simulation of the livestock sector. This approach addresses the weaknesses of each model with the strengths of the other, enriching the simulation results and providing a more accurate depiction of the dynamic interplay between herd dynamics and economic factors.

To evaluate the linkage's efficiency and simulation accuracy, we introduce a shock related to animal mortality. The rationale for considering this shock is that it significantly influences livestock sector resilience, impacting production outcomes, market dynamics, and farmers' livelihoods. High mortality rates pose economic losses and food security risks at household and national levels, reflecting underlying health issues within livestock populations. By integrating animal mortality scenarios, our study aims to reveal their implications on Tanzania's livestock production, trade, and livelihoods. Understanding mortality rate effects is crucial for policymakers and stakeholders to devise interventions enhancing sector resilience and farmer welfare.

***Keywords*:** Animal mortality, Dynmod, GAMS, Multi-market Partial Equilibrium

Introduction

Understanding the complex dynamics of the livestock sector is paramount for policymakers, researchers, and stakeholders who aim to enhance sector resilience and improve farmer livelihoods. The livestock sector, characterized by its multifaceted interactions between biological processes and economic factors, requires sophisticated modeling approaches to capture these dynamics accurately. In this context, two pivotal models have emerged: the Dynmod model and the multi-market partial equilibrium model, also known as SectorM.

The Dynmod model is renowned for its ability to simulate complex herd dynamics over time. It systematically represents various factors, including offtake rate, mortality rate, parturition rate, age, sex, size, and other demographic attributes. This detailed representation allows for an in-depth analysis of herd structure and population changes, providing valuable insights into the biological aspects of livestock management. However, a notable limitation of Dynmod is its assumption of constant prices and economic variables during simulations. This assumption, while simplifying the modeling process, restricts the model's capacity to reflect the dynamic economic conditions that are inherently present in the real-world livestock sector.

On the other hand, the SectorM model excels in capturing economic complexities by considering prices and other economic variables as endogenous. This approach enables SectorM to simulate how these variables evolve based on a range of influencing factors. By incorporating economic dynamics, SectorM provides a robust framework for analyzing market behaviour (including demand and supply dynamics), trade flows, and policy impacts within the livestock sector. Despite its strengths, SectorM's representation of herd dynamics and demographic factors is less detailed compared to Dynmod, potentially limiting its ability to capture the biological complexities of livestock management fully.

Recognizing the complementary strengths and weaknesses of Dynmod and SectorM, this paper proposes an innovative approach to integrating these two models. By linking Dynmod and SectorM using the General Algebraic Modelling System (GAMS) software, we aim to create a comprehensive simulation tool that leverages Dynmod's detailed herd dynamics and SectorM's economic adaptability. This integrated model is designed to provide a more realistic and holistic representation of the livestock sector, capturing the dynamic interplay between biological processes and economic conditions.

This research chose Tanzania's livestock sector as its case study because of its significant role in the country's economy and susceptibility to various shocks, including animal mortality. Animal mortality is a critical factor influencing livestock sector resilience, with profound implications for production outcomes, market dynamics, and farmers' livelihoods. High mortality rates can lead to substantial economic losses and food security risks, highlighting the need for effective interventions to mitigate these impacts.

To evaluate the efficiency and accuracy of the integrated model, we introduce a shock related to animal mortality. This shock serves as a test case to examine how the combined strengths of the Dynmod and SectorM models can enhance our understanding of the effects of mortality rates on the livestock sector. By simulating scenarios of increased animal mortality, the study aims to reveal the broader implications for Tanzania's livestock production. Specifically, the study assumes a 70% increase in the mortality rate in 2022, from the business-as-usual mortality rate of 8% in the Dynmod model to approximately 13.6%.

The findings of this study demonstrate that linking the Dynmod and SectorM models yields intuitive and insightful results. The integrated model reveals that various economic conditions exhibit a dynamic nature over time, indicating responsiveness to changes in economic variables. This dynamic responsiveness contrasts with the static trends observed in the standalone models (i.e., before the models were linked), highlighting the enhanced realism and adaptability introduced by the integration. By capturing the interplay between biological and economic factors, the linked model provides a more accurate and comprehensive understanding of the livestock sector's behaviour under different scenarios.

Moreover, the findings show that an increase in mortality rate exerts substantial negative impacts on livestock-related products, particularly reducing the supply of bovine meat. However, this reduction in meat supply has affected the trends of quantity, prices, and income from the products differently in the linked Dynmod and SectorM models. Specifically, the trends of livestock products, such as meat supply, are more intuitive in the

Dynmod model due to its proficiency in capturing herd dynamics. Conversely, the trends of prices and income are more intuitive in the SectorM model, as it considers the interactions of demand, supply, and trade of livestock products.

The findings suggest that linking the models enables policymakers to design and implement more effective policy interventions to promote sustainable development in the livestock sector rather than relying on standalone models. This research has important implications for decision-making processes aimed at enhancing the sustainability and resilience of the livestock sector. By providing a more accurate depiction of how economic and biological factors interact, the integrated model supports better-informed policy interventions and strategic planning. This improved understanding is crucial for developing targeted measures that can enhance sector resilience, improve farmer welfare, and ensure the stability of livestock production and markets in Tanzania and beyond. By addressing the limitations of standalone models and leveraging the strengths of both Dynmod and SectorM, the integrated approach offers a comprehensive framework for analyzing the impacts of various shocks on the livestock sector, essential for devising strategies that mitigate risks, optimize resource allocation, and contribute to the sustainable growth and development of the livestock industry.

The remainder of the paper is organized as follows: Section 2 provides a review of the literature. Section 3 discusses the overview of the models. Section 4 describes the data. Section 5 explains the implementation of the model linkage. Section 6 presents the results and discussion. Finally, Section 7 concludes the paper.

Literature review

Linking models is a common practice in economic analysis to enhance the robustness and credibility of various modeling approaches. One prevalent example is the integration of computable general equilibrium (CGE) models with other specialized models. CGE models are widely used to analyze policy impacts across sectors and regions, capturing broad economic trends such as population growth, productivity changes, and shifts linked to climate change or energy transitions. However, this broad scope often sacrifices sectoral detail and explicit representation of biophysical processes, which can be better addressed by partial equilibrium (PE) models and sector-specific models. By linking CGE models with PE models and other specialized sectoral models, analysts can achieve a more comprehensive and detailed understanding of economic phenomena, ensuring that sectoral intricacies and biophysical constraints are adequately represented. This integrated approach not only enhances the overall quality and credibility of the analysis but also provides a more nuanced and informed basis for policy decision-making.

Considering the advantages of model linking, several papers have attempted to quantitatively demonstrate the limitations of standalone CGE models and the benefits of integrating these models with others. For example, Kaya et al. (2017) apply constant elasticity of substitution (CES) functions in general equilibrium integrated assessment models (GE-IAMs) to substitute technical factor inputs, such as replacing fossil fuels. Their study reveals that CES functions often fail to match historically observed energy transition dynamics. This is because CES-based approaches are highly sensitive to the structure of their implementation (nesting) and parameter choices. As a result, they can lead to unrealistic projections, such as the over-reliance on fossil fuels with carbon capture, biomass, and nuclear energy in future energy supply scenarios. Furthermore, these models can produce artefacts like monotonically increasing marginal abatement costs of carbon and the substitution of energy with non-physical inputs, such as knowledge and capital, without conclusive evidence supporting such extensive substitution. The authors propose alternative formulations, including perfect substitution for alternative energy options or dynamically variable elasticity of substitution, to address these issues. However, they emphasize that the most effective solution involves complementing economic analysis with physical modeling that accounts for storage and resource availability at high spatial and temporal resolutions.

Other studies, such as Krook-Riekkola et al. (2017), illustrate that linking a CGE model to an energy model for baseline projections in Sweden results in significant changes in the economy's structure and energy use compared to standalone CGE projections. Differences in substitution possibilities for energy sectors and energy-intensive industries between the CGE and the linked model led to considerable variations in production costs, energy use, and broader economic structural changes. Similar studies on climate policy analysis have shown that standalone

CGE models can significantly overestimate or underestimate macroeconomic mitigation costs compared to linked approaches that better reflect "real-world" substitution possibilities (Fujimori et al., 2019; Lanz and Rausch, 2011). Additionally, Britz and Hertel (2011) compare a standalone CGE simulation of global land use and greenhouse gas (GHG) emission impacts due to EU biofuel mandates with a linked agricultural PE-CGE simulation. They conclude that the standalone CGE results overestimate GHG emission impacts by nearly 20 per cent, highlighting the importance of linked models for more accurate policy assessments.

The existing literature indicates that researchers have utilized various approaches to link models. Many studies highlight CGE linkages with PE models, especially in the agricultural and energy sectors. However, since both CGE and PE models capture policy impacts through market interactions, some CGE models are linked with biophysical models, such as crop growth or simple climate models, to account for ecological impacts. Other studies demonstrate the linkage between CGE models and both PE and biophysical models. Additionally, CGE models can be integrated into a larger assessment framework consisting of multiple models (e.g., Crespo del Granado et al., 2018).

Furthermore, the literature emphasizes two key arguments for linking models instead of integrating them into a “super-model.” First, it preserves the comparative advantage of each model type concerning resolution, response time, result quality, and implementation. In other words, each model can excel in what it is specifically designed to do. Second, allowing for differences in methodological and technical solutions, parameterization, and underlying data sources enhances flexibility in model development, application, and maintenance (e.g., Britz, 2008).

Over time, the variety of model-linking approaches has expanded, complicating comparisons and evaluations. Amidst this complexity, the literature commonly discusses two main approaches: soft-linking and hard-linking. However, there is no standardized definition for these terms. According to Wene (1996), soft-linking involves direct user control over the processing and transfer of information between models, which may introduce subjective judgment errors. In contrast, hard-linking formalizes information processing and transfer between models through computer programs, ensuring a more structured and automated approach.

Regarding the flow of information, the literature discusses two main approaches: one-way and two-way linkages. In a one-way linkage, outputs from one model act as exogenous shocks to another model. This approach can be categorized as top-down or bottom-up depending on whether information flows from a sectoral or global model into a biophysical model, or vice versa. In contrast, a two-way linkage incorporates feedback between models, facilitating better convergence. In a comparative-static model setup, convergence in two-way linkages occurs through iterative solutions, where information transfer between models persists until a predefined threshold is achieved (Delzeit et al., 2020).

Despite a number of research efforts focusing on linking models within the agricultural sector, particularly with crop growth models and global models such as CGE models, there remains a noticeable gap in the literature concerning the linkage of models within the livestock sector. This gap is surprising given the pivotal role of the livestock sector in promoting sustainable development, influencing outcomes such as livestock systems, poverty alleviation, food and nutrition security, and the sustainable management of natural resources. Comprehensive and integrated models capable of capturing these multifaceted dynamics under different economic conditions are essential yet underrepresented in current research endeavours.

Hence, this study addresses a crucial gap in the literature by linking two models primarily focusing on the livestock sector: the Dynmod model and the multi-market partial equilibrium model (also known as SectorM). The study evaluates the impact of a significant shock, specifically animal mortality rates, on livestock sector production and productivity. It compares the results from the standalone and linked versions of the models. One reason for focusing on animal mortality rates is their significant adverse impact on the livestock sector. For example, a study by Ahmed (2023) evaluates the economic impacts of livestock disease outbreaks on Tanzania's agricultural sector, demonstrating that such outbreaks significantly diminish agricultural GDP, livestock production, and exports, leading to substantial economic losses. Additionally, the study highlights that these disease outbreaks cause income reductions for farmers and pose threats to food security and overall economic stability.

Furthermore, this study specifically examines Tanzania's livestock sector, with a focus on cattle, as a case study. The rationale for selecting Tanzania includes the critical role of livestock in its GDP and the availability of comprehensive data. For instance, according to Michael et al. (2018), Tanzania accounts for about 1.4% of the global cattle population and 11% of Africa's cattle population. Additionally, beef constitutes 82% of red meat production in Tanzania, underscoring the sector's importance to the country's economy. The following section provides a detailed description of the models considered in this study: the Dynmod and SectorM models.

Overview of the models

The Dynmod model simulates the dynamics of livestock population size and the annual number of animals produced. It also calculates live weights, meat production, and secondary products such as milk, skin, hides, and manure at the population level. Additionally, Dynmod provides financial outputs that can be integrated into more comprehensive financial calculations, such as benefit-cost ratios or internal rates of return. The model also offers crude estimates of the population's feeding requirements in terms of dry matter.

The initial version of Dynmod was developed jointly by CIRAD (Centre de coopération internationale en recherche agronomique pour le développement) and ILRI (International Livestock Research Institute) in 2007 (Lesnoff, 2008). Since the release of the first version, the Dynmod model has undergone significant updates. For instance, it has been converted from an MS Excel version to a GAMS version, which is utilized in this study.

Furthermore, the Dynmod model incorporates economic conditions such as the price of live animals and other commodities. However, Dynmod assumes constant prices over the simulation period, which contrasts with real-world conditions where prices and other economic factors can fluctuate due to changes in demand and supply. This assumption of constant prices is one of the major drawbacks of the Dynmod model, limiting its ability to capture the economic dynamics of the livestock sector fully.

Moreover, the SectorM model is a recursive-dynamic, deterministic partial equilibrium model that employs a mixed complementarity problem (MCP) to calculate equilibrium values, such as demand, supply, and trade of livestock-related products. The SectorM model comprises 13 equations, including those for crop area, crop yield, crop supply, livestock supply, food demand, feed demand, commodity inflow and outflow inequalities, domestic trade inequality, import and export inequalities, and import and export quotas. The SectorM model represents a country within its regional administration. It considers commodities like maize, which both humans and animals can consume. In this study, the SectorM model represents Tanzania across seven regional units and considers maize as animal feed. For livestock products, the study focuses on bovine meat from smallholder, fattening, and peri-urban systems.

Both models share attributes such as a recursive-dynamic nature and one-year projection time steps, fostering an environment conducive to effective model linkage. However, they differ significantly in model types, objectives, and geographic and sectoral scopes. Dynmod, a growth model, excels in representing production systems, animal age and sex categories, and herd dynamics, including fertility and mortality and offtake rates, albeit with a more aggregated perspective. On the other hand, SectorM, a partial equilibrium model, internally calculates prices and lacks explicit herd dynamics but compensates with regional specificity. Unlike the Dynmod model, the SectorM model considers prices that vary over the simulation period, responding to changes in economic conditions such as market demand and supply.

This complementary nature of the two models suggests that the strength of one could address the weakness of the other. Therefore, combining these models harnesses their strengths, contributing to a more comprehensive analytical framework that this study aims to demonstrate. Table 1 highlights the key differences and similarities between the Dynmod and SectorM models, providing insights into their distinct attributes.

Table 1: Comparative Overview of Dynmod and SectorM Models

Attributes	Dynmod	SectorM
Model type	Growth model	Partial equilibrium model considering mixed complementary programming model (MCP)
Overall objective	Projection of herd dynamics	Equilibrium values for supply, demand, and prices of livestock products.

Geographic scope	Aggregated regional representation (Tanzania)	Tanzania is divided into seven regions + Rest of the world
Sectoral scope	Small, medium, and large-scale bovine cattle production across 4 systems: Grass-based (3 systems) Mixed rainfed (3 systems) Mixed irrigated (3 systems) Peri-urban dairy (2 systems)	Three production systems producing bovine meat: Smallholder systems Fattening (medium) systems Peri-urban (large) systems
Time dimension	Recursive-dynamic	Recursive-dynamic
Time horizon	2013-2033 years, further disaggregated into monthly time steps	2016-2028
Price of commodities	Exogenously determined (fixed) over time	Endogenously determined (a function of production) and varies over time
Herd dynamics	Accounts a detailed animal age, sex and size, reproduction rate, mortality rate, offtake rate, and other demographics.	Herd dynamic is not accounted for.

Source: Adopted from Bahta and Asfaw (2023).

Data description

Both models utilize data sourced from various primary and secondary sources. Additionally, data collection and quantitative diagnostics were supported by the continual involvement of key national livestock experts and consultations with a wide range of stakeholders.

The Dynmod model organizes data into four major categories. The first category is herd data per production (farm) system, which includes variables such as annual parturition rate, net rate of prolificacy, percentage of females at birth, initial herd size, mortality rate, offtake rate, and age distribution by sex of animals. The second category encompasses production data per production system, including milk (in litres), meat (in kg), hides and skins (in kg), wool (in kg), manure (in kg), and animal draught power (in pair-day/year).

The third category includes expenditure data per production system, covering costs associated with digestible dry matter feed, concentrates, forage production, grassland maintenance, consumables and small equipment, taxes and contributions, domestic costs for economic analysis (including family labour, land capital, and transhumance costs for pasture and water), and loans for working capital. The fourth category comprises income data per production system, detailing income from selling livestock products directly to consumers and through intermediaries within the value chain. Additional details about these variables and their sources can be found in Michael et al. (2018).

The SectorM model also relies on data from various sources, focusing on variables such as crop area, crop yield, crop supply, livestock supply, food demand, feed demand, commodity inflow and outflow quantities, domestic trade volumes, import and export volumes, import and export quotas, per capita income, and population size. It also employs data on market parameters, including the conversion ratio from producer weight to consumer weight, processing costs (as a fraction of consumer price), commodity transportation cost adjustment factor, extra cost of processing for export, and feed-meat conversion ratio. A detailed description of each variable and its data sources is discussed in Bahta et al. (2021).

Implementation of the Model Linkage

As discussed in Section 2, the literature provides various methods for linking models. This study opts for a two-way linkage approach, as articulated by Delzeit et al. (2020), where information flows bidirectionally between models. In line with this approach, the study establishes a robust linkage between the Dynmod and SectorM models, as depicted in Figure 1.

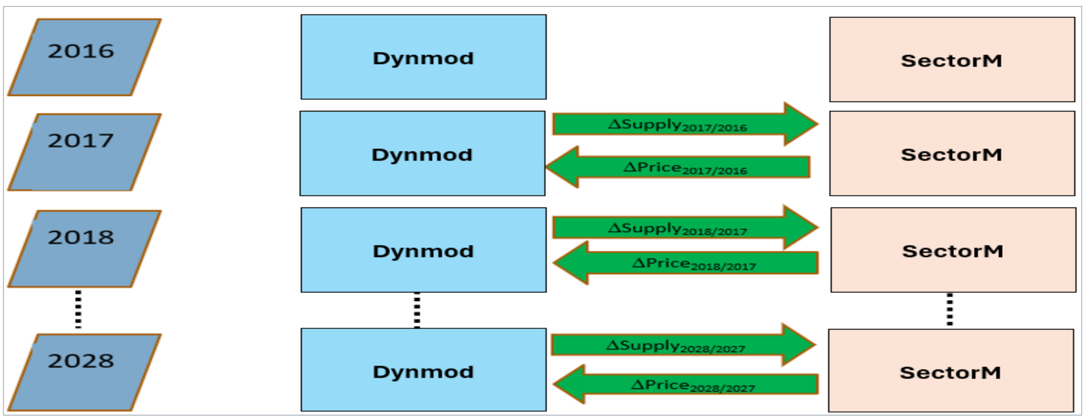
The two-way linkage framework facilitates iterative information exchange between Dynmod and SectorM. This setup allows each model to influence and update variables within the other model, creating a mutually reinforcing dynamic. Dynmod, focusing on livestock population dynamics and production outputs, provides data on herd dynamics, production yields, and economic inputs to SectorM. In turn, SectorM processes this data to determine market equilibria, trade volumes, endogenously determined prices and economic impacts at a regional level. These outcomes are then fed back into Dynmod to refine livestock production and economic forecasts.

Figure 1 visually illustrates the integrated two-way linkage between Dynmod and SectorM. It outlines the flow of information and feedback loops between the models, demonstrating how variables and outputs from one model influence those in the other. This integrated approach enhances the accuracy and robustness of economic and agricultural forecasts, offering insights crucial for policy assessments and scenario analyses related to the livestock sector dynamics in Tanzania. This integrated modeling framework not only improves the precision of economic forecasts but also enables nuanced evaluations of policy interventions and their impacts on agricultural and economic outcomes.

Figure 1 demonstrates that the initiation of information exchange is set in 2017, as the percentage change of exchanged values (for example, the percentage change of prices) in 2016 compared to 2015 is unavailable. The sequence begins with the Dynmod model, which, upon solving for 2017, transmits the percentage change in bovine meat supply to the SectorM model. Within SectorM, this information manifests as a supply shock, affecting variables such as the price of livestock products. Subsequently, after solving for 2017 with the supply shock from Dynmod, SectorM reciprocates by conveying information on price change to Dynmod in the form of a price shock. This reciprocal information flow persists until the conclusion of the predetermined time horizon, extending to 2028. This coordinated exchange ensures a dynamic and interlinked simulation between Dynmod and SectorM, capturing the intricate dynamics of bovine meat production and market responses over the specified period.

Furthermore, the integration of Dynmod and SectorM models enables us to introduce various types of shocks or scenarios at any point during the simulation period. In this study, we focus on the impact of animal mortality rates, which negatively affect bovine meat production in Tanzania's livestock sector. Specifically, we assume a 70% increase in animal mortality rates in the year 2022. The authors determine this assumption, but it does not reflect an actual increase in mortality rates within Tanzania’s livestock sector. The primary purpose of this study is to link the Dynmod and SectorM models and analyze how the results change before and after the linkage. Additionally, we aim to examine the effectiveness of the model linkage by assessing whether the trends of the variables affected by the animal mortality rate are responsive to the shocks after the model linkage and consistent with real-world conditions.

Figure 1. The process of model linkage between Dynmod and SectorM.



Source: Adopted from Bahta and Asfaw (2023).

The pathways through which the assumed shock (i.e., animal mortality rate) influences the variables include reducing the number of animals in the herd, reducing the number of offtake animals, and consequently, decreasing the supply of bovine meat. This reduced supply acts as a shock in the SectorM model, impacting the equilibrium price of bovine meat. The altered equilibrium price in the SectorM model is then fed back into the Dynmod model as a shock, creating a dynamic interplay that captures the intricate relationships between herd dynamics and economic factors over time.

By incorporating this two-way linkage framework, the study enhances the accuracy and robustness of economic and agricultural forecasts. This integrated approach offers valuable insights for policy assessments and scenario analyses related to livestock sector dynamics in Tanzania. Figure 1 visually illustrates the integrated two-way linkage between Dynmod and SectorM, outlining the flow of information and feedback loops between the models, and demonstrating how variables and outputs from one model influence those in the other. The following sections provide the results from before and after the model linkage.

Results and discussions

Pre-linkage results in Dynmod and SectorM models

Before delving into the post-linkage results, it is important to provide the trends of the variables affected by the shock (i.e., animal mortality rate) under a business-as-usual scenario (or without simulation). This baseline helps compare their trends after the model linkage and evaluate how they respond to the shocks. By comparing these baseline trends with the post-linkage results, we can better understand the effectiveness of the model integration and its ability to capture real-world dynamics.

Accordingly, Figure 2 depicts the price of live animals (offtake value in Tanzania shillings per animal) and the price of bovine meat (Tanzania shillings per kg). Figure 2 shows that the trends of these variables remain constant over the simulation period, as they are assumed to be constant, highlighting one of the major drawbacks of the Dynmod model. This static assumption fails to reflect the real-world market fluctuations, emphasizing the need for a more dynamic and responsive modeling approach, which is addressed through the integration of Dynmod with the SectorM model.

Figure 2: Pre-linkage offtake value and bovine meat price in the Dynmod Model

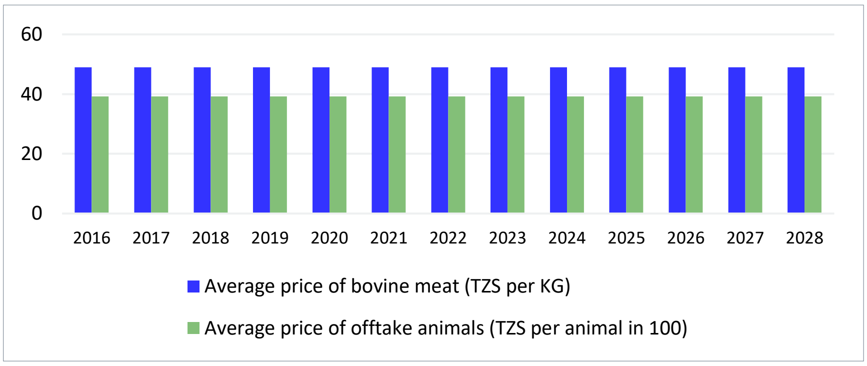


Figure 3 illustrates the pre-linkage total bovine meat supply derived from the offtake animals (in million kg) in the Dynmod model. The figure indicates that Tanzania's livestock sector experiences an increasing trend in bovine meat supply over the simulation period. This suggests a positive outlook for meat production under the business-as-usual scenario, assuming no significant disruptions. The increasing trend in meat supply shown in Figure 3 highlights the potential for growth within the Tanzanian livestock sector. This trend is driven by stable or improving conditions related to animal health, reproduction rates, and management practices. However, it's important to note that this optimistic projection assumes that there are no major shocks or disruptions to the system, such as disease outbreaks, severe weather events, or significant changes in market conditions. Understanding this baseline scenario is crucial for policymakers and stakeholders to plan and implement strategies that can sustain and enhance the sector's productivity.

Figure 3: Pre-linkage Supply of Bovine Meat (in million kg) in the Dynmod Model

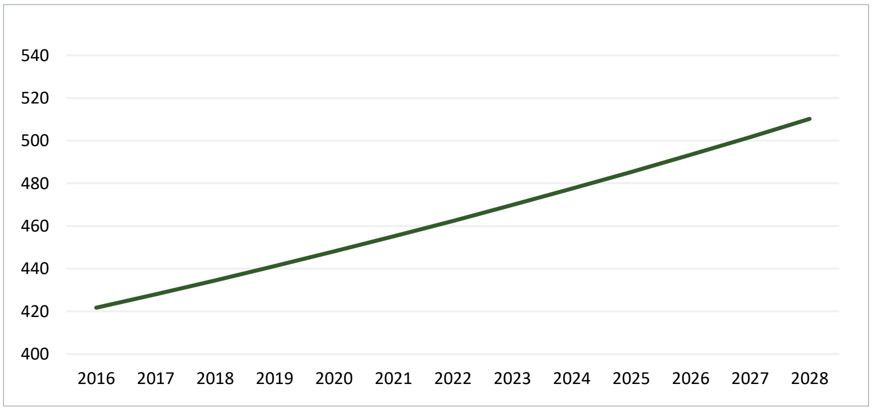
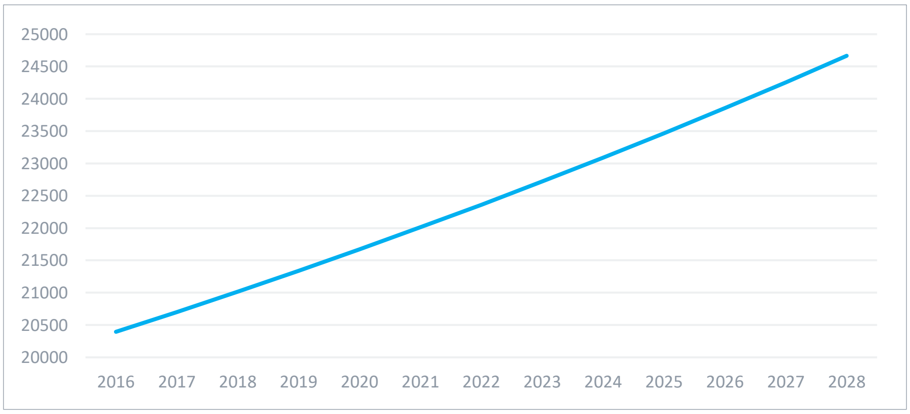


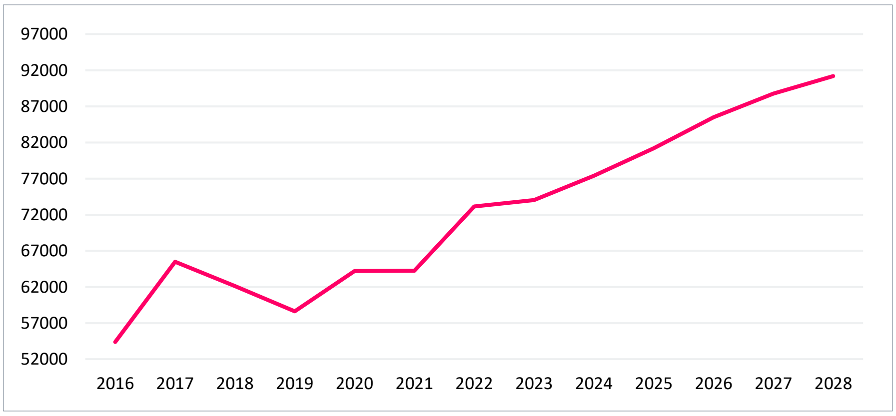
Figure 4 shows the pre-linkage income from bovine meat (in million TZS) in the Dynmod model. As depicted in Figure 5, the income from bovine meat follows a consistent and significant upward trajectory. However, it can be argued that such a steady increase in income might not be achievable in the real world due to several influencing factors, including environmental and economic conditions. For instance, the price of meat may not remain constant over time as assumed by the Dynmod model (as shown in Figure 2). Instead, it may fluctuate due to factors such as changes in market demand, supply chain disruptions, climatic conditions affecting livestock health and productivity, and broader economic variables such as inflation or currency fluctuations (e.g., Odongo et al., 2022). These real-world dynamics suggest that the assumptions in the Dynmod model, particularly the exogenously determined constant price, may not reflect a realistic trend of income from bovine meat. Therefore, linking models like Dynmod with those that account for these fluctuations, such as SectorM, can provide more accurate and practical insights for policymakers.

Figure 4: Pre-linkage Income from Bovine Meat (in million TZS) in the Dynmod Model



Regarding pre-linkage trends of variables in the SectorM model, Figure 5 illustrates the equilibrium price of bovine meat (per KG in TZS), determined endogenously through the interaction of equations described in Section 3. Unlike the steady increase observed in the Dynmod model (Figure 2), the price of bovine meat in the SectorM model fluctuates due to factors such as changes in demand, supply, exchange rates, and both domestic and international trades within the SectorM framework. This variability mirrors real-world market conditions influenced by market dynamics, policy changes, and external economic factors. For example, Nigatu et al. (2020) emphasize the significant impact of global demand and supply dynamics, GDP growth rates in developing economies, fluctuations in agricultural production by major countries like the United States, and changes in global commodity trade volumes on agricultural commodity prices.

Figure 5: Pre-linkage Bovine Meat Equilibrium Price (per KG) in the SectorM Model



Moreover, Figure 6 shows the pre-linkage meat supply (in 1,000 tons) in the SectorM model. While the trend of bovine meat supply depicted in Figure 6 is consistent with Figure 3, it does not account for crucial livestock parameters such as offtake rate, mortality, parturition rate, prolificacy rate, and the proportion of female animals in the herd, unlike the Dynmod model. Specifically, the data on bovine meat supply in the SectorM model is sourced from secondary sources, which may be prone to biases associated with the reporting and recording of the data.

In contrast, the Dynmod model calculates bovine meat supply "internally" by incorporating parameters like offtake rate, mortality, parturition rate, prolificacy rate, survival rates, and the proportion of female animals. This approach ensures a more accurate and comprehensive representation of livestock dynamics. Consequently, it is scientifically and empirically advantageous to rely on bovine meat supply data derived from a model that integrates multiple factors rather than secondary sources that may introduce data quality issues.

Therefore, linking the models allows us to transfer the bovine meat supply data from the Dynmod model to the SectorM model, which is a key objective of this study. This integration enhances the accuracy and reliability of the projected results, leading to more robust and informed policy and research outcomes.

Figure 6: Pre-linkage Total Supply of Bovine Meat (in 1000 tons) in the SectorM Model

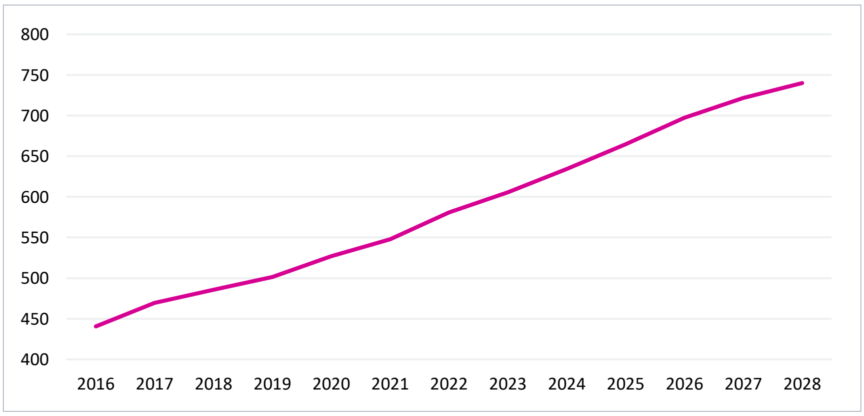
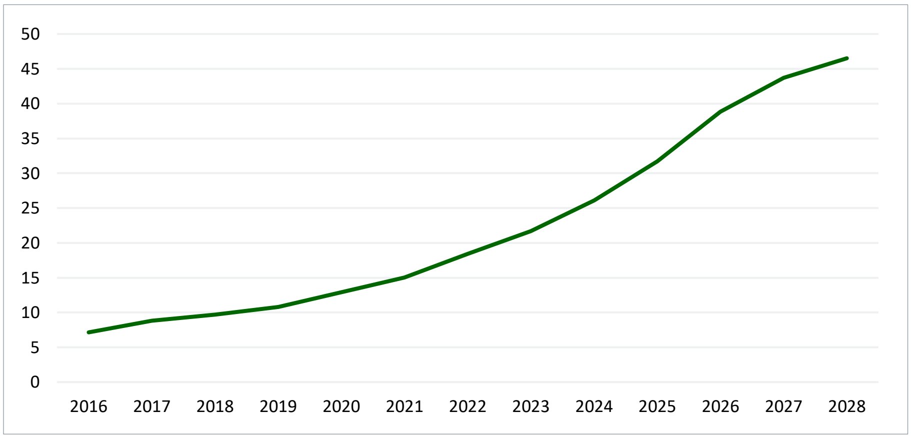


Figure 7 illustrates the total income from bovine meat (in billion TZS) in the SectorM model. Unlike the steadily increasing income trends depicted in Figure 4, Figure 7 shows fluctuating income trends that closely correspond to the price trends shown in Figure 5. This pattern aligns with real-world conditions, where fluctuations in livestock product prices can significantly impact farmers' incomes and, consequently, their livelihoods.

These income fluctuations underscore farmers' vulnerability to market dynamics and external economic factors, highlighting the importance of effective policy interventions. By understanding these trends, policymakers can design and implement strategies that stabilize farmer incomes and promote sustainable livelihoods in the agricultural sector (e.g., Wossen et Al., 2018). Thus, the analysis provided by the SectorM model is crucial for informing decisions that support farmers and enhance their economic resilience.

Figure 7: Pre-linkage Total Income from Bovine Meat (in billion TZS) in the SectorM Model



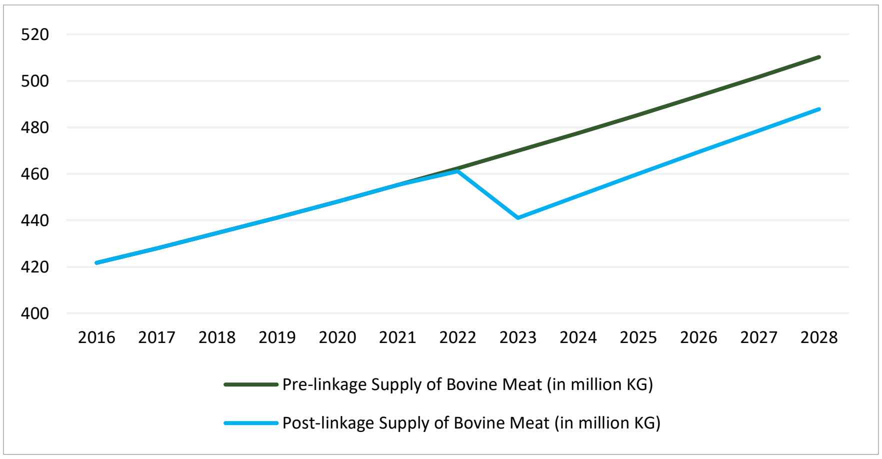
Figures 2 to 7 illustrate the strengths and weaknesses of the Dynmod and SectorM models, demonstrating how they can complement each other. As discussed earlier, this study uses a shock that can significantly affect the dynamics of the livestock sector, specifically the animal mortality rate in the Dynmod model. In the business-as-usual scenario, the Dynmod model considers an average animal mortality rate of around 8% in the Tanzanian livestock sector. In the simulation scenario, the study finds a 70% increase in the mortality rate in 2022, resulting in a rate of approximately 13.6%.

It is important to note that the Dynmod model allows for the introduction of a shock for specific animal age groups (e.g., juvenile, subadult, and adult) and sex groups (male and female). This capability supports policymakers in designing and implementing tailored policy interventions. However, for this study, a 70% increase in the animal mortality rate is applied across all animal categories. The following section provides post-linkage results for the variables discussed in the prior section.

Post-linkage results in Dynmod and SectorM Models

For ease of comparison, this section provides the pre- and post-linkage trends in one graph. Such an illustration can give us a better understanding of the changes in the trends of the same variables before and after linking the models. Accordingly, Figure 8 demonstrates the pre- and post-linkage supply of bovine meat in the Dynmod model. Figure 3 and Figure 8 show that the pre-linkage supply of meat experiences a continuous increase over the simulation period. However, Figure 8 also depicts that the supply of meat potentially decreased starting from 2022, which was caused by the increased mortality rate of animals in that year. This highlights the relevance of utilizing the Dynmod model in examining the effects of biophysical and environmental factors on the herd dynamics of the livestock sector and related products, as the variables respond to the shock (increased mortality rate), which is consistent with theoretical and empirical arguments.

Figure 8: Post-linkage Supply of Meat in the Dynmod Model

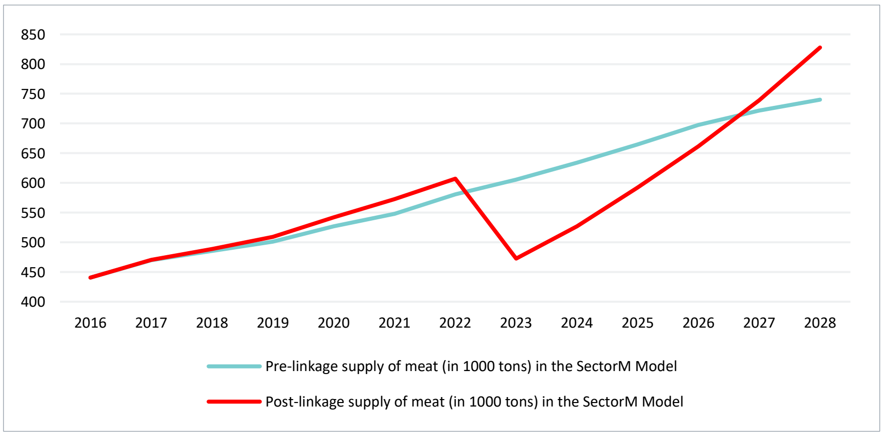


Next, the meat supply shock caused by the increased animal mortality rate is introduced as a “supply shock” in the SectorM model. Unlike the Dynmod model, the SectorM model does not capture various parameters crucial for determining herd dynamics, such as parturition, fertility, mortality, and offtake rates. Figure 9 shows the post-linkage supply of meat in the SectorM model. This figure illustrates that the post-linkage supply of meat responds to the shock introduced by the Dynmod model in 2022, highlighting the importance of linking the models rather than relying solely on standalone models.

Furthermore, the post-linkage supply of meat in Figure 9 incorporates the essential parameters that determine the long-run dynamics of the livestock sector and related products, as seen in the Dynmod model. Figure 9 shows that the SectorM model appears to "underestimate" the bovine meat supply in the Tanzanian livestock sector when comparing the overall trends of pre- and post-linkage supply of meat.

Specifically, before the shock occurred in 2022, the post-linkage supply of meat was greater than the pre-linkage supply. Additionally, as the mortality rate's effect decreases over time, the post-linkage meat supply overtakes the pre-linkage supply, particularly after 2027. This evidence suggests that policymakers should use the Dynmod model to design and implement policy interventions aimed at promoting the herd dynamics of the livestock sector, as it factors in various essential parameters determining these dynamics.

Figure 9: Post-Linkage Supply of Bovine Meat (in 1000 Tons) in the SectorM Model



The decrease in the supply of meat shown in Figure 9 leads to a reduction in the equilibrium quantity supplied and demanded of meat in the SectorM model. However, the effect of these reductions on the equilibrium price depends on the magnitude of the reductions in both the equilibrium quantity supplied and demanded. To compare and examine these magnitudes, we calculated the percentage changes in the equilibrium quantity supplied and demanded of meat in the SectorM model after the models were linked (i.e., post-linkage).

Figure 10 shows the percentage changes in the equilibrium quantity supplied and demanded of meat in the SectorM model. It illustrates that the percentage change in the equilibrium quantity supplied of meat is greater than the percentage change in the equilibrium quantity demanded. In other words, the magnitude of the reduction in the equilibrium quantity supplied is greater than the reduction in the equilibrium quantity demanded. This difference leads to a shortage of meat, resulting in an increase in the equilibrium price of meat (e.g., Ramsey et al., 2021; Ijaz et al., 2021). Consistent with this evidence, the study reveals that the post-linkage equilibrium price of meat has risen notably, especially after 2022, in the SectorM model, reflecting a substantial meat shortage, as depicted in Figure 11.

Figure 10: Percentage Changes in Equilibrium Quantity Supplied and Demanded of Meat in the SectorM Model

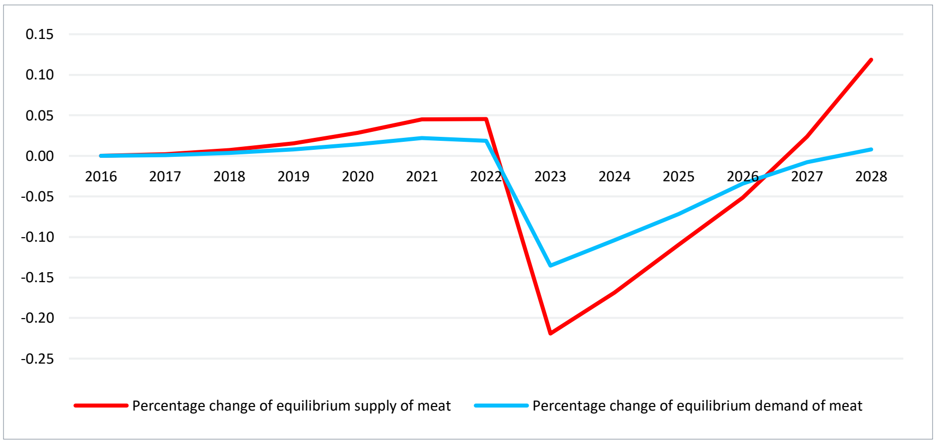


Figure 11 displays both the pre-linkage and post-linkage equilibrium prices of meat in the SectorM model. As seen in Figure 11, the post-linkage equilibrium price exceeds the pre-linkage price, indicating an increase likely due to the significant shortage of meat. Moreover, Figure 11 illustrates the percentage change in the equilibrium price of meat. This percentage change serves as a "price shock" introduced into the Dynmod model, impacting the prices of offtake animals and bovine meat, which were assumed constant throughout the simulation period (as depicted in Figure 2).

Figure 11: Post-Linkage Price of Meat in the SectorM Model

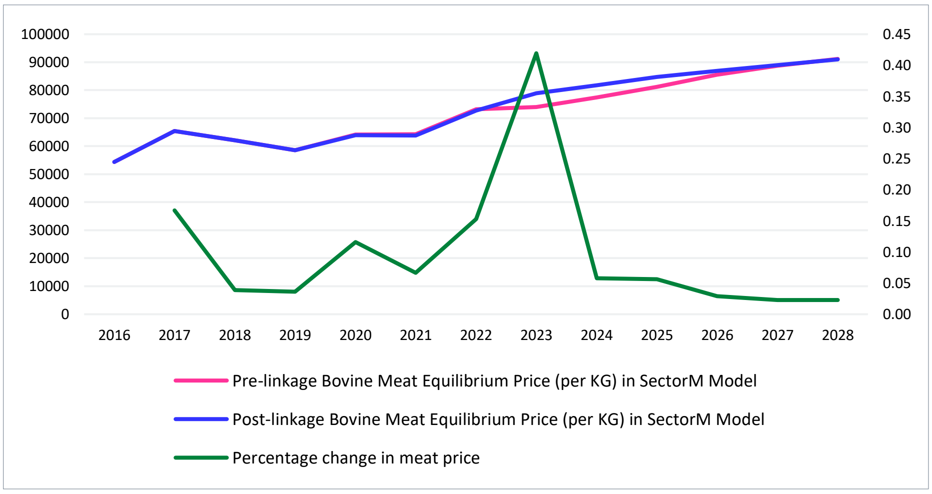
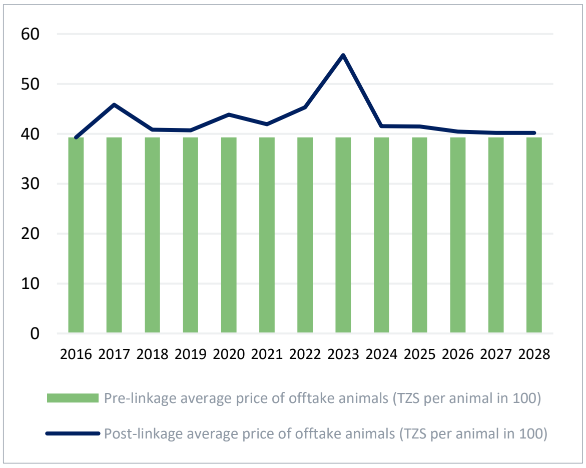
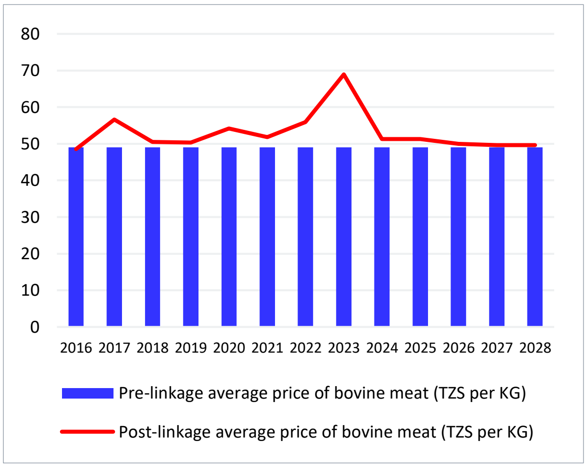


Figure 12 illustrates the pre- and post-linkage prices of offtake animals and bovine meat in the Dynmod model, demonstrating their variations over time in response to the price shock introduced from the SectorM model. These variations highlight how post-linkage prices dynamically respond to real-world conditions, reflecting fluctuations influenced by diverse economic and market factors rather than remaining static.

This evidence underscores the critical importance of integrating the Dynmod and SectorM models. While each standalone model may overlook key livestock-related parameters, their linkage enables a more comprehensive understanding and simulation of livestock sector dynamics. This integration ensures that the models generate theoretically and empirically consistent results, thereby enhancing the reliability of policy recommendations and decisions. Such policy interventions are essential for increasing the sector's contributions to food security, poverty reduction, and overall economic development.

Figure 12: Post-Linkage Prices of Offtake Animals and Bovine Meat

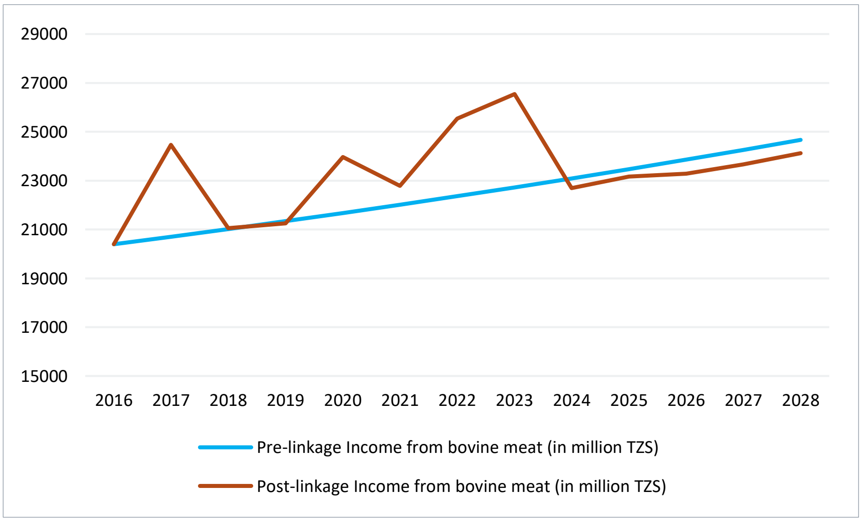




To further evaluate the effectiveness and underscore the importance of linking the models, we employed two approaches. Firstly, we examined the impact of the "price shock" introduced from the SectorM model on income from bovine meat in the Dynmod model, which showed continuous growth before the models were linked, as depicted in Figure 4. Subsequently, Figure 13 illustrates the post-linkage income from bovine meat in the Dynmod model. The figure reveals that income from meat does not exhibit a consistent increase over the simulation period, reflecting real-world conditions where income can fluctuate due to various economic factors, including changes in meat prices, as shown in Figure 12.

Additionally, Figure 13 indicates a decline in income from bovine meat, particularly after 2022, coinciding with a 70% increase in animal mortality rates. This trend contrasts with the findings in Figure 11, where a larger reduction in the equilibrium quantity supplied compared to the quantity demanded led to a meat shortage and subsequent price increase. Normally, such a price rise would be expected to boost meat income. However, the Dynmod model does not reflect this trend comprehensively. The discrepancy arises because the Dynmod model does not fully capture market dynamics, such as demand, supply, and trade of livestock products, despite its proficiency in modeling parameters that influence livestock sector dynamics.

Figure 13: Post-Linkage Income from Bovine Meat in the Dynmod Model

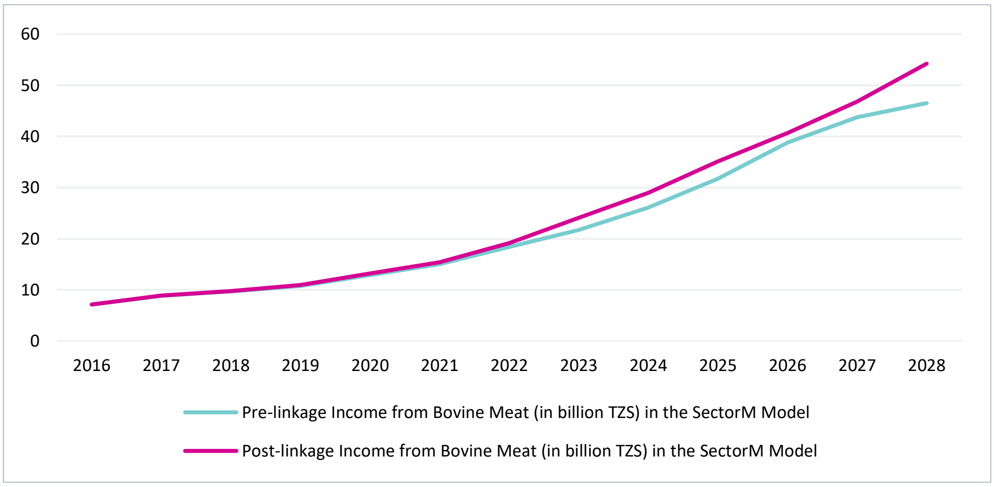


Secondly, we examined the impact of the "supply shock" introduced from the Dynmod model on meat revenue in the SectorM model. Figure 14 presents the post-linkage revenue from meat in the SectorM model. Unlike Figure

13, Figure 14 consistently shows that post-linkage revenue from meat exceeds pre-linkage levels, particularly after 2022. This increase in revenue is primarily attributed to the higher equilibrium meat prices resulting from meat shortages due to increased animal mortality rates.

The SectorM model consistently produces theoretically and empirically sound results, especially regarding the dynamics of demand, supply, and trade of livestock products, as detailed in the 13 equations described in Section 3. This robustness underscores the value of integrating models to analyze and predict livestock sector dynamics accurately, informing effective policy interventions aimed at promoting sustainable development, enhancing food security, reducing poverty, and fostering overall economic growth.

Figure 14: Post-linkage Income from Bovine Meat (in billion TZS) in the SectorM Model



Overall, these results highlight that integrating Dynmod and SectorM models yields more robust and practical insights for policymakers. It allows for a more comprehensive analysis of the livestock sector's dynamics, facilitating the design and implementation of effective policy interventions. Such integrated models are essential for addressing the complexities of livestock production and market interactions, ultimately supporting sustainable development, food security, and economic growth in the livestock sector.

Conclusion

This study has demonstrated the significant advantages of linking the Dynmod and SectorM models to understand better and manage the complexities of the livestock sector in Tanzania. By integrating these models, we can capture both the biological and economic dimensions of livestock production, providing a more holistic and accurate representation of sector dynamics. The findings reveal that while standalone models have limitations in addressing certain variables, their integration offers a comprehensive framework that enhances the realism and reliability of the projections.

The introduction of a mortality rate shock, resulting in a 70% increase in the mortality rate, served as a critical test case for the integrated model. The results indicate that such a shock leads to substantial impacts on the supply of bovine meat, prices, and income from livestock products. The Dynmod model, with its strength in capturing herd dynamics, effectively illustrated the reduction in meat supply, while the SectorM model provided a more intuitive understanding of the resulting price and income fluctuations. This complementary use of both models underscores the necessity of their linkage to develop effective policy interventions.

Furthermore, the integrated model revealed the dynamic nature of various economic conditions over time, contrasting with the static trends observed in the standalone models. This dynamic responsiveness to changes in economic variables highlights the enhanced realism and adaptability introduced by the integration of the models. By capturing the interplay between biological and economic factors, the linked model provides a more accurate and comprehensive understanding of the livestock sector's behaviour under different scenarios, offering valuable insights for policymakers.

In conclusion, the integrated model supports better-informed decision-making processes, enabling policymakers to design targeted interventions that enhance the sustainability and resilience of the livestock sector. The insights gained from this study highlight the importance of considering both biological and economic factors in policy formulation. By addressing the limitations of standalone models and leveraging their combined strengths, this approach offers a robust framework for analyzing the impacts of various shocks and stressors. This comprehensive understanding is crucial for optimizing resource allocation, mitigating risks, and ultimately contributing to the sustainable growth and development of the livestock sector in Tanzania and beyond.

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