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# Modelling the Dynamic Interaction between Production Growth and Carbon Footprint of Livestock Sector in Ethiopia

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**Abstract:** Livestock is the largest agricultural subsector, supporting the livelihood of many populations and the economy in Ethiopia. The sector is, however, a significant contributor to the carbon footprint in the country. Only direct emissions from the sector accounted for more than 36% of total emissions. Thus, the purpose of this study is to model and evaluate the livestock production system and its contribution to the carbon footprint. A system dynamics model that represents the livestock production system and its interaction with the environment in Ethiopia has been built. The simulated results have demonstrated that increasing meat productivity through improvement in feed quality and supply, increasing slaughter, managing land use change, and implementing price policy have a sound effect on lowering greenhouse gas emissions (GHG) while also improving the supply and value of meat. The policy scenario has achieved 15% and 11% growth in meat and livestock value, respectively, while reducing greenhouse gas emissions by 40% compared to the base case in 2040.

*Keywords: livestock, carbon footprint, system dynamics, Ethiopia*

## Introduction

In Ethiopia, livestock forms the majority of agriculture which supports the livelihood of the majority of the population as well as the country's economic development (Boka, 2020). The sector contributed 26% to the agricultural gross domestic product (GDP) in 2021 (National Bank of Ethiopia [NBE], 2021), and 20% to the gross domestic product (GDP) and foreign exchange earnings (World Bank, 2017). Besides, households rely on the sector as a key supply of food and nutrition, a source of income, plough farmland and protection against crop failure (Fantu, Bart, Fanaye, & Taffesse, 2018; Prasad, Dean, & Alungo, 2022; Raney, Skoet, & Steinfeld, 2009a; Wieland, 2019).

The country has the largest livestock population in Africa with around 70 million cattle, over 52 million goats, 42 million sheep, 56 million chickens, and 1.6 million camels in 2020 (FAO, 2020d). The estimated value of tropical livestock units (TLU) is 51 million units in the same year (FAO, 2020f). The production system is distributed over the highland regions, where livestock production is subordinate to crop production, and the pastoral and agropastoral lowland regions, where livestock production dominates the other agricultural activities (Food and Agriculture Organization [FAO], 2020; Nell, 2006). However, these huge resources have been underutilized due to market inefficiencies, livestock feed shortages, disease, and low productivity (Food and Agriculture Organization [FAO], 2017).

Livestock is also increasing in value over time. The estimated value was 3.95 billion US dollars in 2010 and hit 5 billion US dollars by 2020 (FAO, 2020e). However, this growth is solely due to the increase in the livestock population and not because of productivity improvement (Philip K. Thornton, 2010). Livestock productivity is hampered by factors such as, but not limited to, a lack of access to and adoption of better technology, seasonal and poor feed availability and quality, market problems, animal disease, and farmers education and awareness (Fantu et al., 2018; Mamo, Mengistu, & Asebe, 2017; Mekuriaw & Harris-Coble, 2021). Although productivity is still a major problem in the country, there is a potential for the country to increase production (Fantu et al., 2018; Shapiro et al., 2015; Tegegne & Feye, 2020).

On the other hand, the expansion of livestock production imposes a significant environmental burden on the country (Kimball, 2011). Livestock is a major source of greenhouse gas emissions and environmental change in the country. In 2018, about two-thirds of the emissions from agriculture, as well as more than 36% of the emissions from the entire country were produced directly by the livestock industry through enteric fermentation and manure production. The sector, through emissions from enteric fermentation and manure production, contributed about 63.9 million tons of CO2-eq emissions in 2010. The emission level has been steadily rising and attained 86.76 million tons of CO2-eq emissions in 2020 (FAO, 2020b). This places the industry among the top emitters in the nation. The amount tends to increase along with the population of livestock in the nation unless some steps are taken to complement the effect on the environment. Inadequate production systems, poor health, and low productivity further exacerbate the emission level (Philip K Thornton et al., 2019).

Furthermore, the sector indirectly contributes to environmental changes through land use change which results in soil erosion, habitat and land degradation, and greenhouse gas emissions (Admassie & Abebaw, 2021; Alkemade, Reid, van den Berg, de Leeuw, & Jeuken, 2013; EFCCC, 2017; Kimball, 2011). Land use change and forestry accounted for 12.5% of total emissions in the country in 2018, with livestock contributing significantly due to larger livestock populations and the sector's reliance on land (Alemayehu, 2013; Climate Watch, 2022).

Livestock feed consumption is primarily dependent on natural resources, with natural pasture accounting for 55% of total feed consumption, followed by crop residue (31%), hay, and other by-products (CSA, 2021). The area used for grazing also increased from 1.37 million hectares in 2004 to 1.77 million hectares in 2015 (Fantu et al., 2018). This indicates that the sector is heavily reliant on the environment, paving the way for overgrazing and, eventually, environmental changes. Conversely, the livestock density is also increasing. There were 1.01 and 1.32 tropical livestock units (TLU) per hectare of agricultural land in 2010 and 2020, respectively. In comparison to the emerging economies and global averages, which are 0.41 and 0.43 tropical livestock units (TLU) per hectare of agricultural, respectively, the country's livestock density is high (FAO, 2020f). This increase in livestock density puts pressure on grazing land and reduces its accessibility (Fantu et al., 2018; Tilahun & Schmidt, 2012). Urbanization and corresponding growth in cropping further reduce the amount of grazing land, which also influences the supply of animal feed (Mekuriaw & Harris-Coble, 2021).

Ethiopia's overall economic growth rate was 5.6% in 2021. Furthermore, population, per capita income, and urbanization have increased at rates of 2.6%, 2.9%, and 4.8% in 2021, respectively (World Bank, 2021). Thus, these faces of rapid population growth, urbanization, and improved living standards all imply higher demand for animal-sourced foods (ASF) and hence livestock production (Bachewe, Minten, & Yimer, 2017; Cheng, McCarl, & Fei, 2022; Minten, Dereje, Bachewe, & Tamru, 2018; Shapiro et al., 2015). This increment in output is achieved, however, through extensive land use change and feed production. This causes a shift in land use, which affects forests, water resources, emission levels, and ultimately, the environment (Wellesley, Happer, & Froggatt, 2015). Overall, the production of livestock in Ethiopia results in both direct and indirect environmental changes. These changes further exacerbate the effect of those environmental consequences. This trend has put social and economic development at risk. As a result, it is more important than ever to address the rising demand and food production while also achieving environmental sustainability of the sector (Kimball, 2011; Raney et al., 2009a).

Recently, countries have attempted to sustain production and consumption by launching development policies. In this regard, the Sustainable Development Goals (SDG) agenda, which was initiated by all United Nations (UN) countries in 2015, emphasizes the importance of environmental sustainability. Africa has also established Agenda 2063 to strengthen and accomplish the Sustainable Development Goals (SDGs) in light of the continent's vulnerabilities (African Union, 2022).

In Ethiopia, the climate resilient green economy (CRGE) initiatives, which were launched in 2011, seek to produce sustainable growth with no net increase in greenhouse gas (GHG) emissions from the base year, 2010 (Federal Democratic Republic of Ethiopia [FDRE], 2011). To further increase the economy's capacity to adapt to and withstand the effects of climate change, the government launched a national adaptation plan (NAP-ETH) in 2017 (Federal Democratic Republic of Ethiopia [FDRE], 2020). The other ten-year plan was initiated in 2020 as part of a home-grown policy change, and developing sustainable production is among the key pillars (Federal Democratic Republic of Ethiopia [FDRE], 2021a). Furthermore, the country has made a nationally determined contribution (NDC) to reduce total emissions. The first nationally determined contribution (NDC) was announced in 2017, and the newly updated NDC was introduced in 2021, to reduce greenhouse gas (GHG) emissions by 68.8% by 2030 (Federal Democratic Republic of Ethiopia [FDRE], 2021b). As the industry with the highest source of emissions, livestock is one of the focus areas of the plans. This study will also contribute to the ongoing development program of a country as a policy input.

In Ethiopia, prior studies on livestock have sought to comprehend the livestock production system, contributions of the sector to the national economy and households, opportunities and challenges of the production and feeding practices, as well as the sector's relationship with the environment (Altaye, Kassa, Agza, Alemu, & Muleta, 2014; Asmare & Mekuriaw, 2017; Fantu et al., 2018; Kochare, Tamir, & Kechero, 2018; Mamo et al., 2017; Yisehak & Janssens, 2014). However, a holistic system dynamics approach has not previously been used to investigate the dynamic interaction of the sector with the environment and evaluate the greenhouse gas contributions (GHG) in production practices. Furthermore, the assessment of an improved livestock production system in achieving higher production and sustaining the environment is overlooked.

Overall, livestock contributes significantly to the social and economic development of the nation. However, the rapid increase in demand and subsequent increase in livestock production, which puts pressure on the environment, has raised concerns about sustainability. Thus, a production system that promotes social and economic well-being without escalating environmental effects is necessary. Accordingly, the goal of this study is to model the interaction of the livestock production system with the environment and to test alternative policy options for the reduction of carbon emission levels in the sector. The study also aimed to investigate and analyse the factors influencing the livestock production system, as well as to identify a sustainable livestock production system that increases food production and economic value while lowering greenhouse gas (GHG) emissions. The study makes an important contribution to the ongoing global and national policy framework regarding the prospects for a sustainable and efficient livestock production system. The application of the system dynamics model to the evaluation of livestock production would also contribute to the limited methodology of earlier livestock sector literature of Ethiopia.

## Review of related literature

Many studies show that the livestock industry is inextricably linked to the environment and natural resources. Despite its variety of socioeconomic advantages, the sector contributed both directly and indirectly to many environmental changes and the depletion of natural resources (Baltenweck, Enahoro, Frija, & Tarawali, 2020; Cheng et al., 2022). For instance, the works of Abbasi and Abbasi (2016); Broom, Galindo, and Murgueitio (2013); Delgado, Rosegrant, Steinfeld, Ehui, and Courbois (2001); M. Herrero et al. (2013) and Philip K. Thornton (2010) concluded that increasing livestock production, which is driven by urbanization, income growth, and population growth, would increase soil carbon levels, food availability, alleviate poverty, and economic growth; however, it also leads to degradation of natural resources such as land and water, and contributes to climate change if the system is poorly managed.

McMichael, Powles, Butler, and Uauy (2007); Stehfest, van den Berg, Woltjer, Msangi, and Westhoek (2013) and Mario Herrero, Thornton, Gerber, and Reid (2009) have revealed that livestock production is responsible for a significant amount of land use change and biodiversity loss, as well as more for than one-fifth of global greenhouse gas (GHG) emissions. Besides, Rojas-Downing, Nejadhashemi, Harrigan, and Woznicki (2017) and Orheruata and Omoyakhi (2007) strengthen that livestock is a major contributor to greenhouse gas (GHG) emissions. According to Bailey, Froggatt, and Wellesley (2014), livestock is a major source of greenhouse gases (GHG) and climate change, and its impact is expected to grow as demand for the products grows. Nonetheless, changes in emission levels pose a risk to the sector by affecting feed production, water availability, and health.

Post et al. (2020), in their study of the effects of livestock production systems, discovered that the production systems are responsible for a variety of adverse effects, including environmental and health issues. The production system has also been responsible for the massive degradation of the land and a decline in environmental quality (Warsame, Mohamed, & Mohamed, 2023). The studies highlighted the need for creating a more sustainable livestock production system to address the issues facing the industry.

Nicholson, Blake, Reid, and Schelhas (2001) found that the livestock sector has a significant impact on biodiversity loss, environmental degradation, soil erosion, and greenhouse gas emissions in developing countries. The study argued that these issues are primarily the result of ineffective production practices and management in least-developed nations. The quality and availability of feed are other major factors that limit the production of livestock in developing nations, particularly in sub-Saharan Africa (Fraval, Duncan, Notenbaert, Mutua, & Thornton, 2021).

In their review of livestock and environment interactions in Asia and Sub-Saharan Africa, Otte, Pica-Ciamarra, and Morzaria (2019) claimed that increased livestock production causes greenhouse gas (GHG) emissions, water stress, land degradation, and loss of biodiversity. The study proposed that effective policies that take into account the trade-offs that exist in the sector and environment should be developed.

In Ethiopia, the system of raising livestock is highly interrelated with and reliant on the environment and natural resources. The potential of the nation and the expansion of its resources in this area would have a significant impact on natural resources and ultimately on the environment. Kimball (2011) has also discussed several environmental effects of the livestock sector. The study showed that an increase in livestock population is causing a variety of environmental changes, such as soil erosion, land degradation, greenhouse gas (GHG) emissions, water pollution, and deforestation in Ethiopia. These growing changes in the environment and climate in the region are further affecting the sector due to its reliance on natural resources (Gashaw, Asresie, & Haylom, 2014).

In their study of smallholder cattle farming in the Metekel zone, northwest Ethiopia, Altaye et al. (2014) found that the main sources of feed are natural pasture, crop residue, preserved hay, and stubble grazing. Mamo et al. (2017) also stated that pasture is the most important supply of feed for livestock in the Gambela region of Ethiopia. Concurrently, Free grazing is the most common feed system in the Gilgel Gibe catchment in Southwest Ethiopia (Duguma, Tegegne, & Hegde, 2012). The studies also noted that low productivity, poor health, and climate change have all constrained the production system.

According to Kochare et al. (2018) crop residue, unmanaged pasture, and trees and shrubs make up the feed system in the Wolayta zone of southern Ethiopia. The nation's feed system has also been made up of agricultural and industrial by-products. Communal grazing land is the most common feed source for livestock production in Ethiopia's rural highlands. Overstocking is primarily caused by an increase in cropland and livestock populations, resulting in environmental changes in the study area (Tschopp, Aseffa, Schelling, & Zinsstag, 2010). Growing livestock populations have also been identified as the primary drivers of land use change in Ethiopia's highlands. This further affected the environment by reducing feed production, crop-livestock productivity, and vegetation loss (Mekuria et al., 2018). Birhan and Adugna (2014) have also identified the main problem of livestock production in Ethiopia is found to be low forage quality and availability, drought, and land degradation.

These works of literature demonstrate that Ethiopia's livestock system is highly interconnected and affects the environment. As a result, the sustainability of the natural resource and the growing contribution to the greenhouse gas (GHG) footprint would be critical considerations in the expansion and production of the livestock sector in the country. This is because the industry's rapid growth eventually leads to unsustainable use of resources and environmental changes. Despite the massive environmental challenges that livestock poses, the research on its mitigation and adaptation is scant (Graham et al., 2022). Furthermore, the existing works of literature have attempted to investigate the prospects and interactions between natural resources and livestock production systems in Ethiopia. However, the relationship between the industry and environmental factors as well as strategies for reducing greenhouse gas (GHG) emissions were not entirely addressed in the literature.

There is a huge opportunity to sustain the livestock production system that supports food production and livelihood while reducing the negative environmental consequences, mainly in developing countries (Paul, Butterbach-Bahl, Notenbaert, Nderi, & Ericksen, 2020). Integrated and simulation-based models are now becoming more applicable to agriculture, and thus to the livestock sector (Patel, Sharaff, & Verulkar, 2022; Ray, 2021). This is because the models incorporate multiple dimensions to provide efficient and sustainable policy decisions (Baporikar, 2021; Mishra, Chauhan, & Sahoo, 2021). Thus, the purpose of this study is to develop a system dynamics model for evaluating the interaction between the livestock sector and the environment, as well as its contribution to carbon emissions in Ethiopia.

## Methods

The study employed system dynamics modelling. The development of the system dynamics model for the issue is based on the analysis and comprehension of the driving forces behind the system of livestock production and their implications on the environment. A system dynamics model is very useful for exploring and simulating the dynamicity, feedback interaction, and prospects of current activities as well as for evaluating an alternative policy case. The model also takes into account the causal relationship between the structure, non-linearity, and delays of the dynamic behaviours of the problem (Azar, 2012; Azar & Vaidyanathan, 2018; Bala, Arshad, & Noh, 2017; McDonnell, Azar, & White, 2013). The system dynamics model would also promote more informed decisions by simulating real-world issues (Al-Masri, Spyridopoulos, Karatzas, Lazari, & Tryfonas, 2021; Duarte dos Santos et al., 2021). Overall, the causal loop diagram and the stock and flow diagram are used to demonstrate the system dynamics model. The former provides a qualitative analysis of the system, while the latter uses quantitative analysis to visualize its workings (Amadei, 2021).

The livestock production sector is broad and complex which necessitates an assessment of livestock production practices, and their socioeconomic and environmental implications. The sector is also dynamic with multiple interrelations with the population, environment, and socioeconomic factors. This is due to the livestock industry's reliance on natural resources and the environment. On the other hand, the sector is also used to supply food and has an economic value in the country. Thus, an integrated model that accommodates the sector's relationship with the human population and environment is required. Furthermore, it is necessary to choose the best course of action in policymaking that can sustain the rising need for livestock production while maintaining environmental effects. As a result, a dynamic simulation model based on the system dynamics model is employed to capture a comprehensive understanding of the complexity and dynamicity of the sector.

The livestock production sector was modelled by taking into account the major ruminants (cattle, goats, and sheep) that are all converted to the tropical livestock units (TLU) in Ethiopia. The structure of the model must correspond to the existing knowledge of the system. Existing related literature has been reviewed to develop the model that reproduces the causal and feedback interaction of the livestock production system and environment in Ethiopia. Data, terminology definitions, and reports from the Ethiopian Statistical Service (ESS) and the Food and Agricultural Organization (FAO) serve as the foundation for developing the sector's production system and its interaction with the environment, particularly in terms of the sector's contribution to greenhouse gas emissions. To quantify and parameterize the variables of the model, ranges of data are gathered from various surveys and reports from both national and international organizations. The model was simulated for a period of forty years, from 2000 to 2040, with the first twenty years serving as reference mode and the remaining twenty years based on the predicted future behaviour of the model. This period has been chosen to assess and stimulate the country's current policy frameworks. Vensim simulation software was used to simulate the model for the intended time.

Finally, the less important flows are reflected in the scarce participation of Inca berry goods in international markets, highlighting a notable weakness of this value chain and the need for the prompt intervention of the public and private sectors to reverse the situation and improve the contribution of the Inca berry to the national GDP.

*Dynamic hypothesis*

The demand for livestock products is increasing over time. This is primarily due to an increase in population and an improvement in the population's living conditions. This ultimately fuels an increase in livestock production. The number of livestock units and their corresponding productivity are the main factors that affect livestock production. In Ethiopia, the livestock output growth is attributed to the growing number because productivity is very low. The availability of feed, feed quality, temperature, and the prevalence of disease are the main factors that influence productivity.

Conversely, an increasing number of livestock units puts a greater strain on the environment. This is because the industry is mostly dependent on the environment, and the increasing number which is driven by the rising demand places a burden on the ecology. The sector affects the sustainability of the environment largely by causing pressure on the land or availability of feed and water, as well as by directly releasing greenhouse gas (GHG) emissions in the form of methane ($CH_4$) through enteric fermentation and manure production. Furthermore, the sector indirectly contributes to greenhouse gas (GHG) emissions through changes in land cover and loss of habitat.

The rising livestock population and the industry's low productivity are the main contributors to the rise in enteric methane emissions produced during production. This increase in the total emission level, which causes the rise in the temperature, further affects the livestock industry by lowering the amount of feed intake and its availability, raising the needed water level for the livestock, and causing death directly and through increased disease prevalence.

*Causal loop diagram (CLD)*

A causal loop diagram depicting how the livestock production system interacts with the environment was created to investigate environmental sustainability, specifically the contribution of the sector to the carbon footprint in Ethiopia. The causal loop diagram shown in Figure 1 below makes an effort to grasp the system structure of the livestock inventory, its interactions with the environmental factors, and the industry's output and economic value.

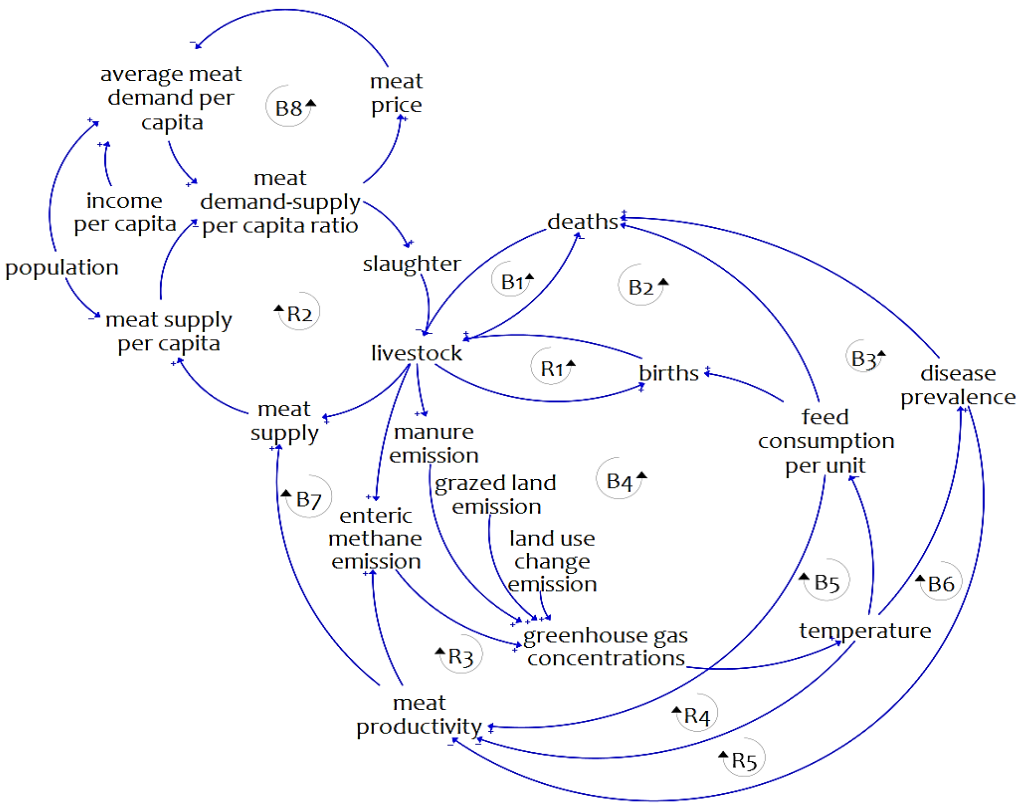


*Figure 1: A causal loop diagram (CLD) representing the model*

The first reinforcing loop R1 indicates that an increase in livestock population leads to more births and hence more livestock. More livestock, on the other hand, leads to more deaths and, eventually, less livestock. This is indicated by balancing loop B1. According to balancing loop B2, as livestock units increase, more emissions are produced through enteric fermentation and manure, resulting in higher greenhouse gas (GHG) concentrations and temperatures. This higher temperature reduces livestock feed consumption, resulting in more livestock deaths.

Feedback loop R2 indicates more livestock units result in higher levels of meat output and lower demand due to increased meat availability. This reduces the number of slaughtered animals and preserves the livestock population. More livestock, according to balancing loop B3, results in higher levels of enteric methane and manure emission, as well as greenhouse gas (GHG) concentrations, which raise the temperature. As a result, disease prevalence has increased, as have deaths, resulting in fewer livestock units. According to feedback loop B4, the greater the number of livestock, the greater the enteric methane and manure emissions, greenhouse gas (GHG) concentrations, and temperature. This higher temperature reduces livestock feed consumption, which reduces livestock births and population.

In feedback loop B7, the more livestock units, the more enteric methane and manure emissions, as well as greenhouse gas (GHG) concentrations and temperature, which reduce meat productivity and supply. Given the growing demand due to population and income per capita growth, lower meat supply leads to an increased gap between meat demand and supply and raises slaughters, which reduces the livestock population. Furthermore, the larger livestock units emit more enteric methane and manure, resulting in higher concentrations of greenhouse gases (GHG) that raise the temperature. Higher temperatures reduce livestock feed intake, meat productivity, and meat supplies. This widens the gap between supply and demand eventually leading to more slaughter and a reduction in livestock numbers. This is indicated by balancing loop B5.

As shown by balancing loop B6, an increase in livestock units causes an increase in enteric methane and manure emissions, as well as greenhouse gas (GHG) concentrations, which raises the temperature. A higher temperature increases disease prevalence, reducing meat productivity and supply. This, in turn, increases the meat supply and demand gap and slaughter, eventually reducing livestock numbers. Reinforcing loop R3 demonstrates that higher greenhouse gas (GHG) concentrations from enteric fermentation, manure and land use change and degradation emissions raise temperatures and reduce livestock productivity, increasing the amount of enteric methane emissions produced. This is because low-productive livestock typically has high emission intensities. After all, enteric fermentation, in particular, is directly correlated with the major factors that lower livestock productivity (FAO, 2019). This contributes to an increase in the level of emissions in the atmosphere.

Higher levels of greenhouse gas (GHG) emissions in the atmosphere, caused directly by enteric fermentation and manure emissions and indirectly by land use change and land degradation, are reinforced by the effect on livestock feed consumption. The more greenhouse gases produced, the higher the temperature, which reduces feed consumption per unit and meat productivity. Heat stress causes livestock to consume less feed, resulting in lower meat productivity (P. Thornton, Nelson, Mayberry, & Herrero, 2022). As a result, enteric methane emissions and greenhouse gas (GHG) concentrations rise. This is denoted by reinforcing loop R4.

A reinforcing loop, R5, demonstrates how rising greenhouse gas (GHG) concentrations lead to higher temperatures, which in turn raise disease prevalence. Higher disease prevalence causes less meat productivity, which increases enteric methane emissions and greenhouse gas emissions. Balancing loop B8 demonstrated that price rises in response to higher demand relative to the supply of meat, which in turn lowers average per capita demand for the meat as well as demand relative to supply.

### *Stock and flow diagram (SFD)*

The system of livestock production stock and flow diagram is shown in Figure 2 below, where the stock and flows are connected to form a structure that defines the behaviour of the system. Five important stock variables are used to create the model. Population is the first stock, and it is changing as a result of the change in the rate of natural increase. This changing population increases the demand for livestock outputs, resulting in livestock production growth. The livestock inventory makes up the other stock and grows as a result of births. The slaughters, and deaths, in contrast, result in a decrease in the livestock unit. These changes in the livestock inventory are directly contributing to greenhouse gas (GHG) through enteric fermentation and manure production in the production process. And indirectly through land cover change and overgrazing of the vegetation.

The population of the livestock and the intensity of their enteric methane emissions, as well as the emission from manure production, are the main factor that contributes to the other stock model variable, the greenhouse gas (GHG) concentrations. A greenhouse gas (GHG) concentration rises due to the increased livestock population and manure production, and high enteric methane emission intensity, which are primarily influenced by the productivity of the livestock. Changes in land use and vegetation loss as a result of livestock expansion are other factors that contribute to greenhouse gas (GHG) concentrations.

The available feed produced from feed production on grazing land, crop residue, and other supplements is also the other noteworthy stock variable. When feed production is high, the amount of feed available raises and it falls when the production is low and temperatures are high. Another stock considered in the model is the availability of water for livestock. It denotes the total amount of water available for livestock in the country. Temperature changes are assumed to have the greatest impact on livestock water consumption. Livestock requires more water at higher temperatures and vice versa.

The stock-flow model requires the specification of equations and parameterization of the variables before running the simulation. The parameters of the model have been collected from the literature and it considered the real values of the system. The initial values and parameters of the model are based on the relevant real knowledge of the sector. The stock-flow model is used to simulate the model after all of the necessary data and equations for the parameters taken into account have been entered. Table 1 below provides a summary of the values of variables and parameters of the model along with information on the unit of measurement and source of the values.

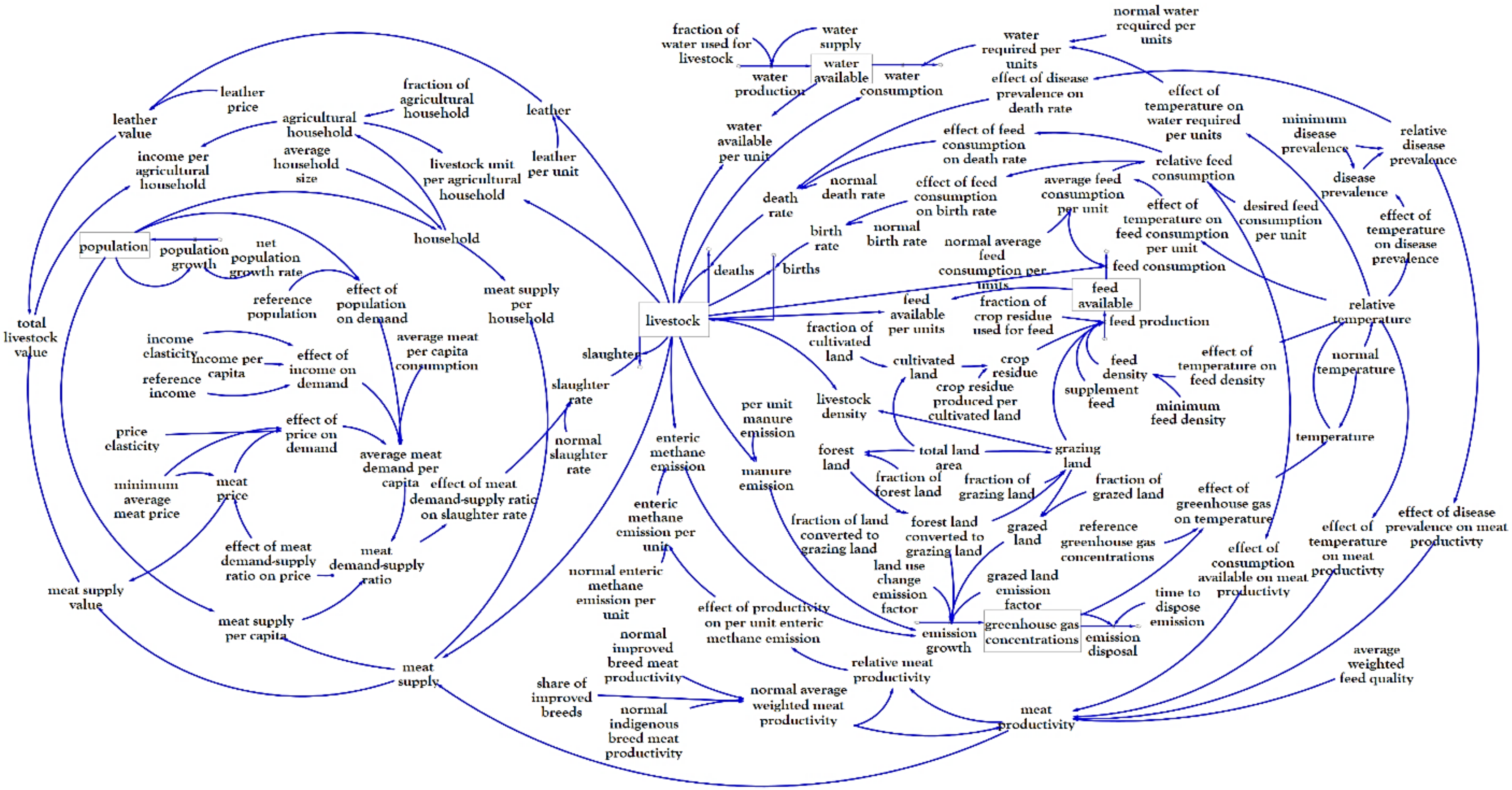


*Figure 2: Stock and flow diagram (SFD) of the model*

*Table 1. Initial and parameters value of the model*

| PARAMETERS | INITIAL VALUE/VALUE | UNIT | SOURCE |
|---|---|---|---|
| Population | 67,031,867 | Person | World Bank (2020b) |
| Water available | 690,000,000,000 | Liter | FAO (2020a) |
| Livestock | 20,684,572 | TLU | FAO (2020f) |
| Feed available | 51,283,692,000 | Kg | (Bediye, Nemi, & Makkar, 2018; FAO, 2016) |
| GHG concentrations | 36,633,150,000 | Kg $CO_2$ | FAO (2020b) |
| Fraction of agricultural household | 61.4 | Dmnl[1] | |
| Average household size | 5 | Person | FAO (2022) |
| Normal birth rate | 22 | Dmnl /Year | |
| Normal death rate | 6.7 | Dmnl/Year | CSA (2021) |
| Normal slaughter rate | 1.9 | Dmnl/Year | |
| Normal disease prevalence | 11.9 | Dmnl | Mekuriaw and Harris-Coble (2021) |
| Normal average meat consumption | 5.3 | Kg/Person/Year | Tafere and Hassen (2012) |
| Desired feed per unit | 2280 | Kg/TLU/Year | Jahnke and Jahnke (1982); Kochare et al. (2018) |
| Average feed consumption per unit | 1596 | Kg/TLU/Year | Abera, Tolera, and Assefa (2014); Tesfay, Gebrelibanos, Woldemariam, and Tilahun (2016) |
| Total land area | 110, 430,000 | Hectare | |
| Fraction of forest land | 12.2 | Dmnl | FAO (2016) |
| Fraction of grazing land | 18 | Dmnl | |
| Fraction of grazed land | 23 | Dmnl/Year | Gebreselassie, Kirui, and Mirzabaev (2016) |
| Fraction of land converted to grazing land | 0.089 | Dmnl/Year | EFCCC (2017) |
| Leather per unit | 17 | Kg/TLU | Adem (2019) |
| Leather price | 10 | ETB/Kg | Shapiro et al. (2015) |
| Minimum feed density | 1,580 | Kg/Hectare | Ayele, Tolemariam, Beyene, Tadese, and Tamiru (2022) |
| Normal per unit enteric methane emission | 1288 | Kg $CO_2$/TLU/Year | Gibbs and Johnson (1993) |
| Per unit manure emission | 53.2 | Kg $CO_2$/TLU/Year | Tadesse and Getahun (2021); Woodbury and Hashimoto (1993) |
| Share of improved breeds | 2.2 | Dmnl | Mekuriaw and Harris-Coble (2021) |
| Normal water required per unit | 9125 | Liter/TLU/Year | Sileshi, Tegegne, and Tsadik (2003) |
| Grazed land emission factor | 15,310 | Kg $CO_2$/Hectare | Atsbha, Desta, and Zewdu (2019) |
| Land use change emission factor | 38,300 | Kg $CO_2$/Hectare | Meragiaw, Woldu, Martinsen, and Singh (2021) |
| Average weighted feed quality | 90.79 | DM | Bayissa, Dugumaa, and Desalegn (2022) |
| Normal indigenous breed productivity | 108 | Kg/TLU | Negassa, Rashid, and Gebremedhin (2011); Tefera et al. (2019) |
| Normal improved breed productivity | 156 | Kg/TLU | Teye and Sunkwa (2010) |
| Supplement feed | 61,416,000 | Kg/Year | Bediye et al. (2018) |
| Water supply | 1,850,000,000,000 | Liter/Year | |
| Fraction of water used for livestock | 34.5 | Dmnl | Water Footprint Network (2016) |
| Normal water required per unit | 9,125 | Liter/TLU/Year | Sileshi et al. (2003) |
| Minimum average meat price | 320 | ETB/Kg | Feed the Future (2017) |
| Fraction of cultivated land | 15 | Dmnl | FAO (2016) |
| Fraction of crop residue used for feed | 60 | Dmnl | Teshager (2019) |
| Crop residue produced per cultivated land | 2,000 | Kg/Hectare | McIntire, Reed, Teḍla, Jutzi, and Kebede (1988) |
| Time to dispose emission | 15 | Year | Defar (2016) |
| Income per capita | 5,743 | ETB/Person/Year | World Bank (2020a) |
| Net population growth rate | 0.03 | Dmnl/Year | World Bank (2020b) |
| Price elasticity | 0.733 | Dmnl | Tafere, Taffesse, Tamiru, Tefera, and |
| Income elasticity | 0.933 | Dmnl | Paulos (2010); Worku and Tafere (2012) |
| Normal temperature | 25 | °C | - |

[1] Dmnl: indicates that the unit is dimensionless

### *Model validation*

A model behaviour test is used to determine how accurately the model produces the reference data (Bala et al., 2017; Sterman, 2000). The four main variables in the study—livestock, meat supply, enteric methane, and manure emission—were chosen to test the model's behaviour accuracy over a given time series of data sets. The historical data is simulated for the years 2000 to 2020. The reference data for livestock and meat supply is based on an estimate from the Food and Agriculture Organization (FAO) livestock and crop production (FAO, 2020d). On the other hand, the reference data for enteric methane and manure emission is retrieved from the Food and Agriculture Organization (FAO) climate change estimation (FAO, 2020c).

Figure 3 below depicts the simulated value of livestock, meat supply, enteric methane emission and manure emission in the country over twenty years in comparison to the historical data. As shown in the graph, the difference between historical data and simulated model value is close to zero. There is no statistically significant difference between the values of simulated and historical data, indicating that the model is a good fit for the real structure.

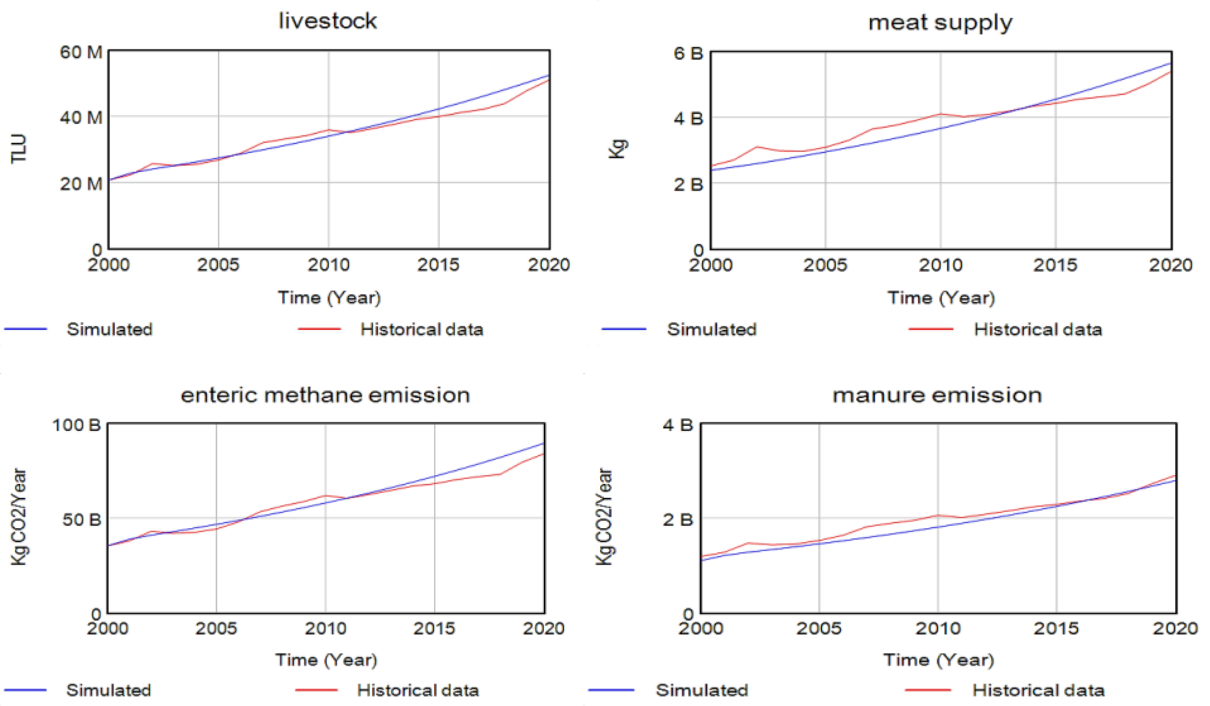


*Figure 1: Simulated and historical behaviour of livestock units, meat supply, enteric methane and manure emission*

Overall, the differences between the simulated results and the reference data are very small in the validation of the main variables. This provides confidence in simulating and analysing alternative future policy scenarios.

### *Sensitivity analysis*

Sensitivity analysis is employed to identify the sensitivity of the results to the changes in the parameters. It is also used to identify the leverage points in the analysis of the relationship between the parameter and results (Bala et al., 2017). A sensitivity test is carried out to identify the most important and relevant variables that might change the results of the main variables.

The study has determined the key parameters that could change and lead to different outcomes of the main variables. Given the factors that affect Ethiopia's livestock production system, it has been determined that changes in meat supply, livestock value, and greenhouse gas emissions depend on parameters such as feed quality and supply, disease prevalence, breed type, slaughter, prices of the products and land use changes. The model considers sensitivity analysis with 50% of the parameter below or above the base case value depicted in the simulated behaviour of chosen variables.

The main variables are primarily found to be highly sensitive to feed consumption per unit, slaughter rate, feed quality, meat prices and a fraction of grazed land, respectively. These sensitive parameters could be taken into account for further policy scenario analysis. However, the main variables are less sensitive to breed type, disease prevalence, forest land conversion, and leather price. Although livestock genetics and breed are among the major constraints of the livestock production system, unless massive investments are made to replace local breeds, it does not result in significant changes to the main variables. This is because the share of improved breed livestock, which includes exotic and hybrid livestock, is as low as 2.2% in Ethiopia (Mekuriaw & Harris-Coble, 2021).

Less sensitivity of the breed type may also indicate that widespread adoption of improved breed types is necessary to significantly change the main variables. In comparison to other parameters, this would be expensive and unfeasible. The main difficulty in implementing significant investment in the adoption of improved breeds could include a lack of resources, innovation, the breeding policy, knowledge dissemination, and a lack of knowledge about the potential livestock resources (Bassa, 2021; Kebebe, 2019; Shapiro et al., 2015). Furthermore, extensive adoption of improved livestock breeds necessitates a long-term and large-scale investment (Haile et al., 2019).

## Simulation and Scenario analysis

### *Scenario design*

Policy scenario planning is a common task in system dynamics modelling for simulating alternative practices and investigating future outcomes. The purpose of this study is to model the interaction of the sector with the environment. In addition, the study also aims to identify the possible policy case that improves the production system while reducing the carbon footprint of the sector. As a result, the model has identified six scenarios, including the baseline and the other five. Growth in meat productivity, land use management, meat productivity growth with slaughter and price policy, and a combination of all policy scenarios are the five scenarios. The simulation period covered the year between 2000 and 2040 and the policy scenarios are activated after 2020.

### *Base case*

The number of livestock continued to rise under the base case. The number has risen over time and is expected to reach 124 million livestock units by 2040. This expansion could be attributed to the reinforcing loop (loop R1) dominance. On the other hand, the concentration of greenhouse gases (GHG) has increased, and the sector's emissions are expected to reach 2.9 gigatons of $CO_2$-eq by 2040. The reason for this includes, among other things, an increase in livestock, land conversion, and degradation, as well as low livestock productivity (Cardoso, 2012; Kimball, 2011). For the simulated period, the supply of meat output and livestock values have both increased. In 2020, the estimated amount of meat was 5.65 million tons, and this figure is expected to rise to 13.39 million tons by 2040. Despite an increase in livestock numbers, the meat supply is increasing gradually because productivity is the main constraint in the production system. The livestock value, which includes the value of meat and leather, has steadily increased in line with the number of livestock. In 2040, the value is expected to reach 19.96 trillion ETB. The value of all the selected main indicator variables has shown a tendency to grow over the simulated period.

Table 2 compares the growth of the selected valuables over the period under the base case.

*Table 2. Summary of the values of main variables under the base case*

| Years | Variables<br>Livestock (in mill) | Meat supply (in bill) | Total livestock value (in trill) | Greenhouse gas (GHG) concentrations (in trill) |
|---|---|---|---|---|
| 2020 | 52.43 | 5.65 | 3.54 | 1.54 |
| 2030 | 80.79 | 8.71 | 8.92 | 2.17 |
| 2040 | 124.28 | 13.39 | 19.95 | 2.94 |
| 2030-2040 | 54.09% | 54.15% | 151.98% | 40.9% |
| 2020-2040 | 137.03% | 137% | 463.56% | 90.9% |

Livestock numbers and meat supply have shown an average growth of 137% between 2020 and 2040 under the base case. This shows most of the growth in the meat supply is only due to the changes in the number of livestock not due to growth in meat productivity. This result is in line with the findings of Fantu et al. (2018), who claim that production growth is solely attributable to livestock growth. Furthermore, total livestock value and greenhouse gas (GHG) concentrations have grown by 463.56% and 90.9%, respectively, for the same period. Although the growth in greenhouse gas (GHG) emissions has shown a tendency to grow slowly, it grows with the livestock population.

### *Scenario 1: Meat productivity growth*

The meat productivity of the livestock production system in Ethiopia is very low. The main causes of low productivity include poor quality and availability of feed for consumption, livestock disease, and temperature changes (Fantu et al., 2018; Ma'alin, Abdimahad, Hassen, Mahamed, & Hassen, 2021; Mekuriaw & Harris-Coble, 2021; Shapiro et al., 2015). Conversely, this low productivity with the larger number of livestock is contributing to the growing greenhouse gas (GHG) emission level both directly and indirectly. This policy aims to strengthen the existing sectorial policy and to test the potential of reducing the emission level through productivity growth. Since productivity is low, increasing the productivity level would have multiple effects. The first is raising the meat supply and the other is achieving the potential reduction of the emissions contributed through enteric fermentation (Enahoro et al., 2019; M. Herrero et al., 2013).

Enhancing breed genetics, feed quality and quantity, as well as the prevention of livestock disease, all contribute to an increase in meat productivity (Mengistu et al., 2021). In this policy scenario, full growth in feed consumption to the desired level and an improvement in feed quality are taken into account to see the full production and emission reduction potential of the livestock sector. Feed consumption per unit and feed quality are chosen because the two parameters are sensitive to changing meat productivity when compared to other parameters.

*Scenario 2: Land use management*

Land use change and habitat degradation caused due to livestock expansion and growth are some of the main factors contributing to the growing greenhouse gas (GHG) emission in the country (Kimball, 2011). Therefore, to maximize the relationship between the growth of production and environmental changes, sustainable land use management in the livestock production system is required (Idel, Fehlenberg, & Reichert, 2013). This policy scenario is tested to reduce the emission that is caused by the conversion of potential forest land and vegetation loss through managing and controlling the grazing and land conversion. This policy scenario took into account regulating and managing all land use changes and overgrazing caused by livestock to determine the maximum capacity that the country could reduce of environmental outcomes.

*Scenario 3: Meat productivity growth with slaughter*

Although there is a growing demand for livestock products, the production and supply of meat and other animal-sourced foods are not satisfying the growing demand (Shapiro et al., 2015). Despite accounting for the majority of agricultural value-added and export revenues, the sector's contribution to household nutrition is minimal in Ethiopia (Tafere & Hassen, 2012). The average off-take rate of major livestock in Ethiopia is estimated to be 22%, which is 8% lower than the potential off-take rate (Nell, 2006). Furthermore, livestock product consumption and utilization are very low. Increasing the off-take and slaughter rate has been critical in improving the livelihoods and nutrition of the households (Jemberu et al., 2022). In addition, to lower the potential greenhouse gas emissions of the sector, balanced growth in livestock also helps to enhance production, protect natural resources, and lower management costs (Cardoso, 2012).

This policy scenario is considered to achieve a higher slaughter rate and production of meat to satisfy the growing need for meat at a lower price while reducing the ecological footprints. Furthermore, this scenario is considered to achieve less greenhouse gas (GHG) emissions by reducing the stock of livestock. The policy scenario took into account increasing the slaughter rate by 8% to produce more meat and achieve low emissions given the country's current low slaughter rate in comparison to the demand for meat.

*Scenario 4: Meat productivity growth with price policy*

In Ethiopia, the marketing and pricing of livestock products are inadequate and poorly managed (Addis, 2017; Shapiro et al., 2015). This scenario takes into account the effect of changes in meat prices. The value chain for livestock and meat products is extensive and complex, with numerous actors involved in its marketing (Dinku, Abebe, Lemma, & Shako, 2019; Solomon, Assegid, Jabbar, & Ahmed, 2003). The sector's poor and long value chain paved the way for the actors to absorb the entire profit of the products (Gadisa, 2022). As a result, farmers do not benefit from the pricing and marketing of livestock products. The main reason is the market's long value chain and a lack of marketing information (Kassie et al., 2019; Tilahun & Schmidt, 2012). Thus, increasing the price of the product would improve the farmer's and the economy's income and livelihoods. However, raising the price is not a sufficient condition for farmers to increase their income; rather, the policy must be delivered alongside well-controlled value chains.

This policy scenario considered a small price change to test how the estimated value of the livestock would improve. Given the sensitivity of the parameter to the total livestock value, a 5% increase in the meat price from the base was considered.

### *Scenario 5: Combination of all policy scenarios*

In this policy scenario, all of the policy cases are activated simultaneously to affect the key model variables. It has considered increasing the productivity of meat production, managing and controlling land use change and degradation, increasing the slaughter of livestock, and raising the price of meat.

The ongoing climate resilient green economy (CRGE) policy of Ethiopia has also advocated increasing the production of livestock products while also increasing the productivity of livestock through the supplementation of feed, raising the off-take rate, improving the efficiency of value chains, and management of grazing and pasture land (FDRE, 2020).

### *Scenario analysis*

The key parameters of the model have been examined in various contexts. The results of the suggested policy scenarios are depicted in the following figures. The nation has the highest population of livestock in all of Africa (FAO, 2020d). Over the simulation period, the livestock population increased in all scenario cases. In comparison to the other scenarios, the meat productivity growth with slaughter and the combination of all policy cases that consider increasing meat productivity while also raising meat prices and slaughtering, as well as managing land use change, has the lowest number of livestock. The number increased from 52 million in 2020 to 82 million tropical livestock units in 2040.

The first and fourth scenarios, which take into account increases in feed quality and supply for consumption, as well as price policy, have shown the greatest increase in livestock numbers. This is because of the fewer livestock deaths and more births as a result of more availability of feed. In Ethiopia, one of the main factors that limited the production of livestock and resulted in the death of many livestock was the lack of feed, especially improved quality feed (Catley, Admassu, Bekele, & Abebe, 2014). Thus, supplementing more and higher-quality feed would boost livestock growth in two ways: one by reducing deaths due to feed shortages and the other by increasing livestock fertility. In the two scenarios, the figure is expected to rise from 118 million in 2030 to 264 million in 2040.

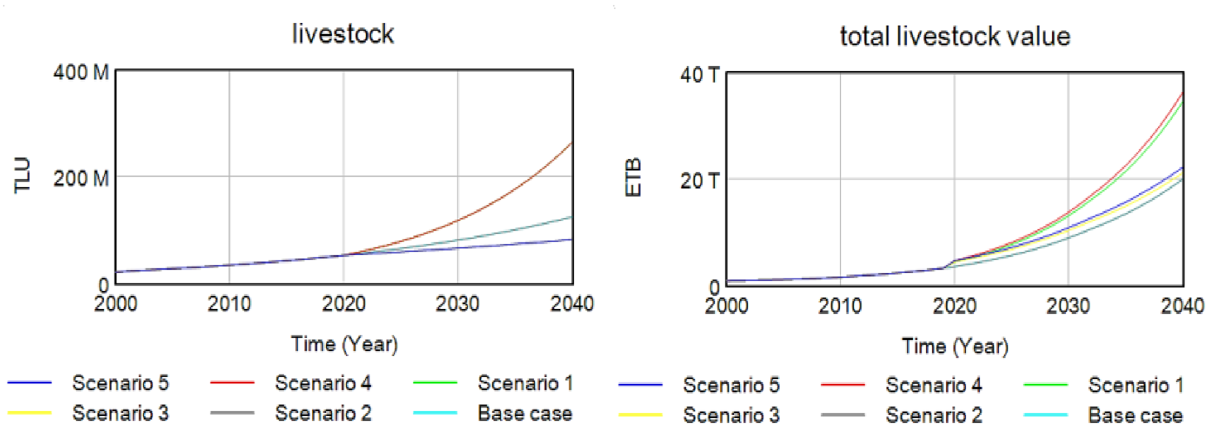


*Figure 2: Livestock and total livestock value under different policy scenarios*

The total livestock value increases rapidly almost under all policy scenarios as indicated in Figure 2. The estimated value has increased under meat productivity growth, meat productivity with price policy, whereas the value slightly growing under the other scenarios. The estimated livestock value has recorded the highest value under meat productivity growth with price policy. The value was estimated to be 14 and 36 trillion

ETB in 2030 and 2040, respectively. The meat productivity growth scenario has also shown higher value with a slight difference from the meat productivity growth with the introduction of the price policy. The value has attained 13 and 34.5 trillion ETB in 2030 and 2040, respectively.

The meat supply, on the other hand, has also demonstrated a similar phase of growth over time. Compared to the other policy scenarios, the meat supply grows at the highest rates under scenarios with rising meat productivity and with the introduction of price policy. Under both scenarios, the amount is anticipated to reach 22 million tons in 2030 and 50 million tons in 2040, respectively. Ayele, Tolemariam, Beyene, Tadese, and Tamiru (2021); Duressa et al. (2014); Grima (2018); Hatew et al. (2023) have also found that improved feed quality and increased feed supply are more effective in increasing livestock productivity and output. Figure 3 also indicated that less meat has been supplied under the base case and land use management scenario. This is due to the low meat productivity of the livestock sector existing in the current production activities of the livestock sector (FAO, 2020d).

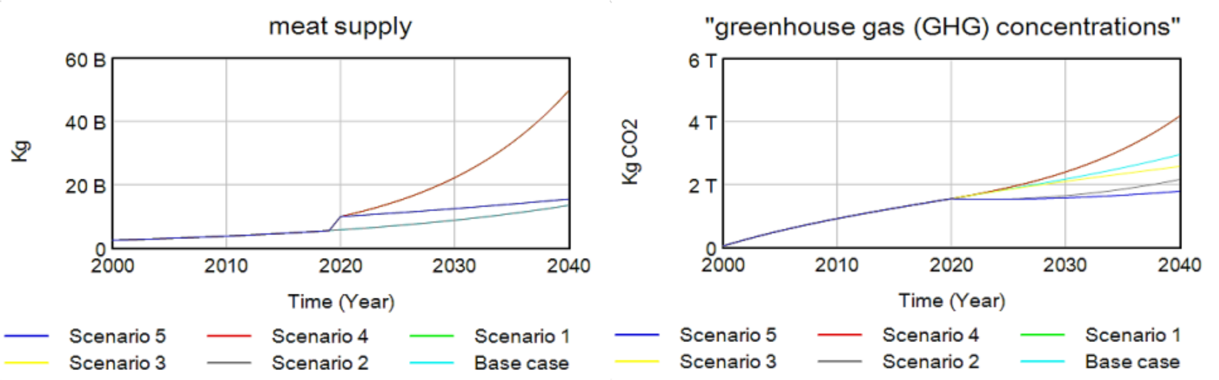


*Figure 3: Meat supply and greenhouse gas (GHG) concentrations under different policy scenarios*

The level of emission increased with different phases under the scenarios considered. In comparison to the base case, the greenhouse gas (GHG) result shows a better result under land use management, meat productivity growth with slaughter, and the combination of all other policies. Introducing the scenario of meat productivity growth, slaughtering, price policy, and managing the land use change to the model is the most effective in reducing the greenhouse gas (GHG) emission as compared to the other policy scenarios. Under this policy scenario, the greenhouse gas emissions have reached 1.6 and 1.8 gigatons of $CO_2$-eq in 2030 and 2040, respectively. This is because improving feed quality and supplementation, and thus meat productivity growth, has the potential to reduce direct emissions (Andeweg & Reisinger, 2014; Caro, Kebreab, & Mitloehner, 2016; Ericksen & Crane, 2018; FAO, 2019; FDRE, 2020). On the other hand, balancing the stock of livestock through slaughtering could also lessen potential emissions from livestock, and consequently, greenhouse gas emissions (Liu et al., 2022) and land use and degradation management, which eradicates indirect emissions, are also policy options for reducing greenhouse gas emissions (Alemu, 2015).

The indirect emission contributed through land use change has also a considerable contribution to greenhouse gas (GHG) concentrations. Thus, the effect of the land management policy scenario has also shown better results in reducing greenhouse gas (GHG) emissions. The emission level has attained 2.15 gigatons $CO_2$-eq in 2040 under this policy scenario. Ravi, Shaw, Boulenger, and Neto (2023) agree that sustainable grazing systems and land use practices should be taken into account to lessen the negative effects on the environment and lower greenhouse gas emissions in the livestock industry.

The rising demand for livestock products, particularly in sub-Saharan Africa, implies that livestock expansion and output supply will continue to rise (Mario Herrero et al., 2009; Philip K. Thornton, 2010). This growth contributes to poverty reduction, improved livelihood, and nutrition (FAO, 2009). However, the expansion of livestock and increased production have negative environmental consequences, particularly the increase in greenhouse gas emissions (Steinfeld et al., 2006). This has revealed that there is a compromise between production and greenhouse gas (GHG) emission levels. The direct relationship between production growth and negative environmental problems in the sector fuels concerns about sectorial management for a sustainable environment. Better and more efficient sector management is required for increased contributions to food and income growth while also reducing the influence on the environment (Enahoro et al., 2019; Otte et al., 2019; Qi, Xin, John, Groisman, & Chen, 2017; Raney, Skoet, & Steinfeld, 2009b). The comparison of the number of livestock, production growth, value of livestock, and greenhouse gas emissions under various scenarios relative to the base case is shown in the Table 3.

*Table 3. Summary of the growth/reduction in the values of the main variables for different scenarios from the base case*

| | Years | Livestock (in mill) | Meat supply (in the bill) | Total livestock value (in trill) | Greenhouse gas (GHG) concentrations (in trill) |
|---|---|---|---|---|---|
| Base case | 2020 | 52.43 | 3.54 | 5.65 | 1.54 |
| | 2030 | 80.79 | 8.71 | 8.92 | 2.17 |
| | 2040 | 124.28 | 13.39 | 19.95 | 2.94 |
| Growth/reduction in relation to the base case (%) | | | | | |
| Scenario 1 | 2030 | 45.69 | 154.29 | 46.77 | 10.43 |
| | 2040 | 112.52 | 270.95 | 72.88 | 41.76 |
| Scenario 2 | 2030 | - | - | - | -24.34 |
| | 2040 | - | - | - | -26.88 |
| Scenario 3 | 2030 | -18.62 | 42.06 | 15.77 | -3.29 |
| | 2040 | -34.17 | 14.91 | 5.94 | -12.76 |
| Scenario 4 | 2030 | 45.69 | 154.29 | 54.09 | 10.43 |
| | 2040 | 112.52 | 270.95 | 81.51 | 41.76 |
| Scenario 5 | 2030 | -18.62 | 42.06 | 21.55 | -27.63 |
| | 2040 | -34.17 | 14.91 | 11.23 | -39.64 |

As demonstrated in Table 3 the growth and reduction of the values of the main variables are compared to the base case growth in values. The greenhouse gas (GHG) concentrations have shown a reduction under land use management policy, meat productivity with slaughter, and a combination of all the scenarios with the reduction of 26.88%, 12.76%, and 39.64% in 2040 as compared to the base case during the same year.

On the other hand, the production growth in meat has also progressed under all the scenarios except with no change in the land use change management policy. The largest meat supply is attained under the meat productivity growth scenario and so under meat productivity growth with price policy. The result has shown a growth of 270.95% as compared to the base case in 2040. About 14.9% growth in the meat supply has been recorded under meat productivity growth with slaughter and combined policy scenarios as compared to the base case in 2040.

As shown in Figure 4, the production of livestock, as indicated by meat supply, has primarily increased under the two scenarios. Meat productivity growth through improved feed quality and supply, as well as the introduction of a price policy to productivity growth, which also increases the estimated livestock value, are two scenarios that have a substantial effect on meat supply. However, this increase in production is not environmentally sustainable because it is not accompanied by a reduction in greenhouse gas emissions.

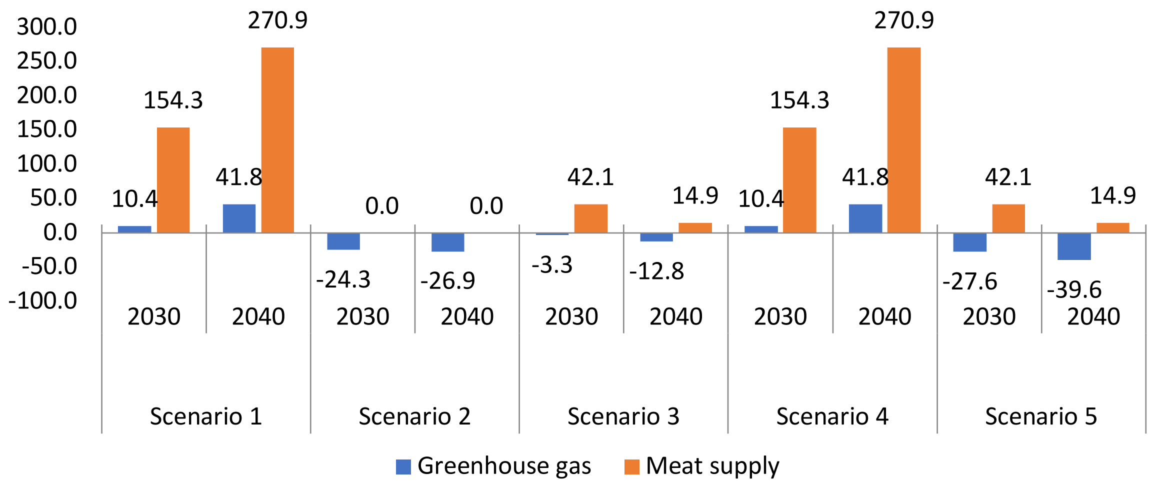


*Figure 4: Production (meat supply) and greenhouse gas growth from the base case*

Livestock expansion is one of the leading causes of land conversion and degradation, which results in environmental changes and greenhouse gas emissions in Ethiopia (Kindu, Schneider, Teketay, & Knoke, 2015). The simulation result has indicated that greenhouse gas reduction has been relatively achieved through land use management, meat productivity growth with slaughter, and the combination of all policy scenarios. As also suggested by Mekuria et al. (2018) and Kimball (2011) better resource management and land use could be better policy choices, to mitigate the negative environmental consequences of the livestock industry.

Under a scenario of managing the indirect emissions caused by land conversion and degradation has the potential to reduce greenhouse gas emissions by up to 27% from the baseline. However, this has been achieved with no change in production and with a lower reduction in emissions than the potential of the sector.

The scenario that incorporates meat productivity growth while also increasing slaughters to balance the potential stock that could produce emissions yields better outcomes in decreasing emissions while also increasing meat production. Activating this scenario would lead to the growth of meat by 42% and 15% than achieved in the base case in 2030 and 2040, respectively. Improved feed that matches livestock nutrient requirements could lead to more efficient and sustainable meat production (Rotz, 2020). Additionally, a synergy of increasing the quantity and quality of feed and preserving land use could increase output and productivity while also promoting an environmentally friendly production system (Mekasha, Gerard, Tesfaye, Nigatu, & Duncan, 2014). The potential emission reduction is also 3.3% and 13% than attained under the base case in 2030 and 2040, respectively.

The scenario that incorporates all of the policy cases from the tested scenarios can be regarded as an effective policy scenario because it achieves the greatest possible reduction in greenhouse gas emissions while also increasing the meat supply over the baseline. In comparison to the base case in 2040, this policy scenario results in a reduction of 40% in greenhouse gas emissions and a 15% increase in the supply of meat. Amsalu and Addisu (2014); (Mekuria et al., 2018) and Tolera and Abebe (2007) also support that increasing the quantity and quality of forage while lowering the mean number of livestock holding as well as sustainable land management could address the sector's environmental problems.

## Conclusion

In Ethiopia, the livestock sector has significant social and economic benefits for households and the country (Boka, 2020; NBE, 2021; World Bank, 2017). However, the growing livestock production driven by rising demand has various negative environmental implications. The industry contributes directly to the increased carbon footprint through manure and enteric fermentation, as well as indirectly through land use change and degradation. Accounting only for direct emissions, the sector is responsible for more than 65% of agriculture and 36% of all national emission levels (FAO, 2020b; Kimball, 2011).

The goal of the study is to model the interactions between livestock and the environment, with an emphasis on the contributions to the carbon footprint. Furthermore, the study intends to test alternative policies for sector production growth and environmental sustainability. A system dynamics model was used to simulate and capture the dynamics and interactions of the livestock industry and the environment. A system dynamics model is also used to analyze and examine the prospects of various policy implementations. The simulated results revealed that the main variables of the model were sensitive to changes in feed quality and supply, slaughter rate, land use change and meat price.

In the current phase of production activities, livestock population, and greenhouse gas emissions would reach 124 million tropical livestock units and 3 gigatons $CO_2$-eq by 2040, respectively. The estimated livestock value and meat supply would also be 13 million tons and 20 trillion ETB by 2040, respectively.

Furthermore, the model was tested against various scenarios to determine the sustainable production system for increasing output while lowering greenhouse gas (GHG) emissions. Scenarios such as land use management, meat productivity growth, meat productivity growth with slaughter and price policy, as well as their combinations, have all been considered.

Higher meat production and livestock value are recorded in the first and fourth scenarios of increased meat productivity through improved feed quality and supply, and meat productivity growth with a well-managed price policy. A lower greenhouse gas emission, on the other hand, is achieved in the first, second, and third scenarios of land use management, increased meat productivity, and meat productivity with slaughter.

The fifth scenario, which combines all of the policies including increased meat productivity through better feed quality and quantity, improved land use management, increased slaughter, and well-managed price policy, has been identified as a leverage policy scenario. The policy scenario is a better option for increasing meat supply and livestock value while lowering greenhouse gas emissions. According to this policy scenario, the amount of meat produced and livestock value both reach 15 million tons and 22 trillion ETB in 2040, respectively, representing increases of 15% and 11% from the base case for the same year. On the other hand, greenhouse gas emissions will reach 1.6 ad 1.8 gigatons CO2-eq emission in 2030 and 2040. As compared to the base case, this value has shown a decrement of 28% and 40%, respectively, in the same year.

Overall, some policy scenarios typically offer higher growth of meat and livestock value than the other scenarios. However, when all of the policy scenarios are combined, a more sustainable production system is achieved. Thus, the study suggests taking into account improving meat productivity levels through increasing feed quality and supplementation, increasing livestock slaughter, implementing the price policy under well-managed value chains, and improving land use management to increase the production growth of meat and its value on the one hand, and to decrease greenhouse gas emissions on the other.

## Implications for future research

This study relies on a comprehensive analysis of the livestock industry at the national level, which may not thoroughly investigate and analyse the unique characteristics of the production system in various agricultural settings. Thus, the report has recommended more research on the country's specific case studies. The distribution, marketing, and supply value chains are not taken into consideration in the analysis of the study. Further research into the distribution and marketing of livestock production has been proposed to better evaluate the workings of the industry. Furthermore, the quality of the meat produced is presumed to be up to standard in the study, which likewise requires more evaluation. Further research is also necessary into the production, gathering, and marketing of the leather industry. The study was also limited in its inclusion of the dynamics of land use change and its interaction with livestock production. Further research is also required to gain more policy insights into land use management.

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