A Partial Equilibrium Model for Analyzing the Economic Burden of Livestock Diseases

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Abstract: This paper develops a partial equilibrium model to assess how improvements in animal disease and livestock health impact the livestock sector of a country's economy. We use empirical data from Ethiopia case study for the small ruminant livestock sector, focusing on meat. Evidence shows that productivity improvement in the live animal sector due to improved animal health is welfare improving down the supply chain. Increases in meat demand, which is projected by the end of this decade, further improve the gains of economic agents across the supply chain. We also show that balancing productivity increase due to morbidity improvement with lower inventory size has the potential to protect farm producers any oversupply problem happening at the short run.

1. Introduction

Livestock contributes to nearly 50% of the global agricultural GDP (Schrobback et al. 2023; Kappes et al., 2023). Households across the world are dependent upon healthy livestock for nutrition and income (DeLay et al., 2020; Kerfua et al., 2023). Livestock diseases are primary constraint in the livestock sector, especially at the farm level as animal diseases are associated with both expenditure increase and output decrease. Consequently, animal health and livestock diseases constrain food security, education, and wealth of households, especially in lower income countries (Hennessy & Marsh, 2021; Marsh et al., 2016; Rushton et al., 2018, 2021). Economic reasoning, models, and measurements can guide investments, programs, and interventions to ensure that resource allocations to the livestock sector are more efficient and sustainable even in the presence of disease externalities (Hennessy & Marsh, 2021; Just et al., 2004; Rushton et al., 2018, 2021).

However, economic losses and costs evaluated only at the farm level does not provide wider economic focus for policy design against diseases. By innovating on the specification of economic burden of animal disease and by broadening the lens to include firms downstream of live animal production along the supply chain and to include consumers, it allows one to assess how improvements in animal health and livestock disease impact the well-being producers and how benefits are redistributed across society at large to consumers (Ramsay et al., 1997).

This paper identifies health changes through livestock production and then applies this concept into a partial equilibrium model to assess how improvements in animal disease and livestock health affect a country's economy. A key contribution of this paper is to illustrate how the impact of improved animal health (i.e., reduced health loss) translates through the input and output markets of a partial equilibrium model, affecting the well-being of a country's economic agents and a specific sector of the economy. We provide empirical evidence from a case study of sheep and goats meat in Ethiopia. As such, the partial equilibrium model complements the use epidemiological models (Gilbert et al., 2024) that generate input for this model to generate economic burden, and also complements the use of a computable general equilibrium modeling effort in Ethiopia (Countryman et al., 2023) that identifies high-level macroeconomic impacts on gross domestic product (GDP) for the entire economy. This is because the partial equilibrium model delineates impacts on the economic well-being of firms along the supply chain, consumers, and total economic welfare.

Partial equilibrium (PE) models have a long tradition in trade and economics, providing estimates of economic efficiency and distributional effects of wealth from exogenous shocks, investments, and policy changes within the same framework (Alston et al., 1998; Wohlgenant, 1993). Partial equilibrium models have been applied to assess animal health or disease shocks. Ramsay et al. (1997), Pendell et al. (2007, 2015, 2016), Rich and Winter-Nelson (2007), and Paarlberg et al. (2008) link supply shocks from an animal disease spread model with a static multi-commodity, multi-market PE model that aggregate trade into total imports and total exports. Zhao et al. (2006), Nogueira et al. (2011), and Tozer et al. (2012; 2015) link livestock disease outcomes to a dynamic model with inventory of cattle that delineates imports and exports by major trading partners. An advantage of using a PE model over a general equilibrium (GE) model is to allow clearer focus along disaggregated aspects along the livestock supply chain and across the agricultural commodities. A disadvantage to using a PE model is that it neglects feedback effects from productivity changes in agriculture to the general economy and disposable household income. The general nature of GE models allows policymakers to gain insights into how a shock to a national or global economy, such as an animal disease outbreak, would transmit throughout all sectors of the economy and the potential reverberations on national income, trade, and employment (Mason-D'Croz et al., 2020).

We specify a vertically integrated partial equilibrium livestock (VIPEL) model to assess how improvements in sheep and goat health alter input (health, feed, and labor) and output (live animal and meat) markets as well as a country's economy. We characterize farm level production under improved animal health for specific counterfactual scenarios defined by animal health loss envelope (AHLE) (Gilbert et al., 2024). We use estimates of input and output shifts of live animal production from global burden of animal disease (GBADs) AHLE epidemiological model to identify production level under improved health conditions. Empirical data from Ethiopian Case Study are used to populate model parameters and to calibrate the model to country level data in 2020. Metrics of economic surplus on firms and consumers are used to quantify the distribution or redistribution of wealth through the meat value chain from changes in animal health. In addition, this static model is linked to livestock inventory to assess supply-inventory tradeoffs and to account for changes in asset wealth.

The paper proceeds in the following manner. First, methods are presented followed by a description of the data from the Ethiopian case study for sheep and goat meat. Then, results are presented followed by discussions and conclusions.

2. Methods

We follow the standard practice by modeling activity of firms along the supply chain to represent supply and by modeling activity of consumers to represent final demand. Our innovation is mostly on the supply side. Let us first begin with the live animal production system as a three-input system.

$$A_s = f^A(L, H, F) \tag{2.1}$$

where A_s is live animal weight, L, H and F are the labor, animal health, and feed inputs, respectively. Note that for a given slaughter class (e.g., sheep or goat), one can link total live animal weight to the breeding herd inventory N by making the simplifying assumption that We define this as:

$$A_s = f^A(L, H, F) = h^A(L, H, F) \times N(L, H, F) \tag{2.2}$$

where $h^A(.)$ is a representative weight per live animal (Gilbert et al., 2024; Paarlberg et al., 2008). We consider both $h^A(.)$ and $N(.)$ exogenous and use the AHLE output as a direct input for the VIPEL model. We assume firms' choice of input and output level is determined by profit maximization principles (Hennessy and Marsh, 2021) where we define the profit function as follows:

$$\Pi = P_A \times f^A(L, H, F) - (P_H \times H + P_L \times L + P_F \times F) \tag{2.3}$$

where Ph_A is the price of output and P_H, P_L, and P_F are the prices of animal health, labor, and feed inputs, respectively. Kuhn-Tucker conditions give us:

$$P_L \geq P_A \times \frac{\partial f^A}{\partial L} \text{ with } L \geq 0 \text{ and } L\left(P_L - P_A \times \frac{\partial f^A}{\partial L}\right) = 0 \tag{2.4}$$

$$P_F \geq P_A \times \frac{\partial f^A}{\partial F} \text{ with F} \geq 0 \text{ and F}\left(P_F - P_A \times \frac{\partial f^A}{\partial F}\right) = 0 \tag{2.5}$$

$$P_H \geq P_A \times \frac{\partial f^A}{\partial H} \text{ with } \mathrm{H} \geq 0 \text{ and } \mathrm{H}\left(P_H - P_A \times \frac{\partial f^A}{\partial H}\right) = 0 \tag{2.6}$$

Moving forward, to focus on health, we assume only the interior solutions for labor and feed, i.e., $L, F > 0$. Health inputs could be considered with both interior and corner solutions depending on the health status. For example, the ideal production state in Gilbert et al., (2024) is defined as $H = 0$. Then Kuhn-Tucker first order condition to characterize this ideal health state must satisfy control of inputs (Marsh et al., 2000). Hence, there is zero demand for health inputs, i.e., $H = 0$. These findings complement Hennessy and Marsh's (2021) damage and abatement specification, which is also applied in Gilbert et al. (2024). If pests or pathogens are not present, then health inputs decrease profit, $\frac{\partial \Pi}{\partial H} < 0$, and this implies that health inputs are zero, $H = 0$. This is the ideal production state wherein disease is not present and production is at its highest potential. Here, increases in health inputs *H* do not increase production but only serve to reduce profit by adding unnecessary expenditures (Railey & Marsh, 2019). In contrast, if pests or pathogens are present, then increases in input *H* can improve profit through production potential, $\frac{\partial \Pi}{\partial H} > 0$, yielding revenue that dominate the additional costs from a positive input level H>0. For positive levels of health inputs, the inverse demand for health input is given by

$$P_H = P_A \times \frac{\partial h^A}{\partial H} \times \mathrm{N} + P_A \times h^A \times \frac{\partial N}{\partial H} \tag{2.7}$$

The first term on the right-hand side of equation (2.7) is the value of the marginal product of health (morbidity) and the second term is the value of the marginal change in inventory due to health (mortality). This last equation expands past research findings and provides the mechanism to link the static partial equilibrium model to livestock inventories.

We also specify behavioral equations for supply of factors, demand and supply equations for meat processors, trade equations for both live animal and meat, consumer demand equation and the market clearing conditions for both the live animal and meat market. For an empirical solution of the model, we take the differential of the equations and then translate the above model into an equilibrium displacement model (EDM). Under this approach, shocks are calculated as percentage changes to be incorporated into the EDM model (see Appendix for details).

2.1. Identification of Ideal Health State

In case of ideal health state, $\frac{\partial f^A}{\partial H} = 0$ since both $\frac{\partial h^A}{\partial H} = 0$ and $\frac{\partial N}{\partial H} = 0$. Hence there is zero demand for health inputs, i.e., $H = 0$. We characterize this ideal scenario with a corner solution where the production technology reduces to a two-input system. Subsequently, input cost share for health go down to zero in the ideal state. Cost shares for health is shown in Table 1. Note that labor cost includes health-related labor costs in the current state, which becomes zero in the ideal state. We account this cost saving by the farm level producer by shocking the labor demand equation. In order to account for the output change, as shown in equation (2.7), we break down the output increase in two parts: the representative weight increase and the inventory increase.

Table 1: Input cost share

Cost Share	**Current**	**Ideal**
Feed cost	12.17%	14.83%
Labor cost	87.28%	85.17%
Health cost	0.55%	0.00%

2.2. Welfare Measurement

Welfare measurement is done via producer and consumer surpluses as in Alston et al., (1995). We also report asset value changes which is calculated by taking the price and inventory change into consideration (Hennessy & Marsh, 2021; Just et al., 2004). We calculate the live animal price change outside of the model by linearizing input demand equation from (2.2). This gives us:

$$EP_N = EP_A + Eh^A$$

Since, inventory, N is kept exogenous from the model, the asset change, for example for ideal state, is calculated as:

$$\Delta Asset_I = P_N(1 + EP_N)N_c(1 + EN_I) - P_N N_c$$

where N_c is the inventory under current scenario and $EN_I = 1 - \frac{N_c}{N_I}$ is the percentage change from the current scenario to the ideal state.

3. Data

Parameters and elasticities used in this study are collected from GBADs AHLE outputs, FAOSTAT, GTAP Database and existing research. Data used are broadly classified into three types: parameters, exogenous linearized variables and level variables for economic surplus calculation.

Table 2: Parameter values and sources used for model simulation

Parameters	Value	Parameters	Value
Domestic share of meat consumption	0.94[a]	Elasticity of substitution between live animal and factors in meat industry	0[b]
Domestic share of meat supply	0.99[a]		
Price elasticity of meat import	3.81[b]	Cost share of labor in the ideal state	86%[c]
Cost share of labor in mortality states	74%[c]	Cost share of feed in the ideal state	14%[c]

Cost share of feed in mortality states	12%[c]	Cost share of health in the ideal state	0%[c]
Price elasticity of meat export	-7.55[b]	Cost share of health in morbidity states	14%[c]
Elasticity of substitution between health & feed	1.12[b]	Elasticity of substitution between labor & feed	1.12[b]
Price elasticity of demand	-1.47[e]	Elasticity of substitution between labor & health	1.12[b]
Price elasticity of labor	1.59[f]	Domestic share of live animal supply	0.99[a]
Price elasticity of feed	3.0[d]	Domestic share of live animal consumption	0.98[a]
Price elasticity of health inputs	3.0[d]	Price elasticity of live animal import	1.98[b]
Cost share of live animal	72%[g]	Price elasticity of live animal export	-1.84[b]

Sources: [a] FAOSTAT, [b] GTAP Database 11, [c] GBADs AHLE Outputs, [d] Assumption, [e] Tafere and Worku (2012), [f] Sakketa and Gerber (2020), [g] DSA

Data used in this study to calculate baseline and economic surpluses are presented in Table 3. It is important to note that while Ethiopia has high inventories of livestock, it only exports about 4% of its total production of sheep and goat meat. Moreover, Ethiopia imports only a small amount of sheep and goat meat. Hence, nearly all the sheep and goat meat produced in Ethiopia is consumed in Ethiopia. However, since we have import component in the VIPEL model, we assign a small share to the import market. From GTAP database, we found Middle East North Africa (MENA) and Sub-Saharan Africa (SSA) are dominant destinations for meat and live animal trade from Ethiopia, respectively. Trade elasticities are calculated from those substitution elasticities using the definition of Allen-Uzawa elasticity of substitution.

Table 3: Data for the baseline and economic surpluses calculations

Variable	**Level value**	**Variable**	**Level value**
Retail Price	7500 USD/ton [a]	Liveweight Price [a]	2378.05 USD/ton
Export of meat	11308.13 tons [b]	Liveweight [b, c]	664090.57 tons
Import of meat	1.46 tons [b]	Per Animal Price [b]	USD 63.22
Domestic Meat Supply	278918.14 tons [b]	Inventory Current [c]	24280021

Variable	Level value	Variable	Level value
Domestic Meat Demand	267611.47 tons [b]	Inventory Ideal [c]	67860356
Inventory Zero Mortality [c]	31893871	Inventory 50% mortality [c]	31843014

Sources: [a] USAID, [b] FAOSTAT, [c] GBADs AHLE Outputs

Prices are calculated assuming that trade and domestic prices are same. For example, farm level output price, i.e., liveweight price, is also the liveweight export price. Similarly, processors' output price, i.e., retail price of the meat and meat export price are equal. Liveweight production is calculated by using the AHLE model parameter for carcass to meat yield. Factor substitution elasticities at the live animal production and meat production are sourced from the GTAP database.

3.1. Scenarios and Simulations

We consider the supply chain of meat from live animal sector to the consumers of processed meat; therefore, we take offtake outputs of number and the liveweight of animals from the epidemiological output. The VIPEL model under consideration breaks down the liveweight production into average liveweight and the number of animals, so we calculate the percentage change of those outputs from the current to the ideal state illustrated in Table 4.

Table 4: Percentage change from current to ideal health state

	(%) change from the current to ideal health state
Offtake Number	16.60%
Average Liveweight	11.61%
Total	28.21%

In the AHLE compartment model proportion of time spent on health-related tasks is 14%, which falls down to 0% in the ideal state. To identify the ideal model within the VIPEL model, a negative exogenous shock of 14% is applied in the labor demand equation to account for the health labor related cost reduction in the ideal state.

Table 4 gives us the characteristics of the benchmark scenario. For Scenario 1, three other cases were considered with 25%, 50%, and 75%, of the benchmark scenario to simulate economic outcomes from the model Table 5. We do this by weighting the improvement in ideal state into both average weight and numbers. We also take into account the weighted save on health-related labor cost.

Scenario 2 is based on increased consumer demand for meat in the form of positive shifts of 15% in retail demand. Notably the growth in global consumption of meat proteins over the next decade is projected to increase by 14% by 2030 relative to 2018-2020, driven largely by income and population growth (OECD, 2021).

Scenario 3 concentrates on the shift in supply and balancing it with inventory in response to the oversupply discussion above. Eshetie et al. (2018) reported that increased meat production in Ethiopia has been due to more animals and not improved productivity. All things held constant, an increase in live weight production is rebalanced with decreased inventory. For example, over the last 20 years, the U.S. live weight ruminant supply increased by about 6% and inventory decreased by about 4%. In the absence of this data for Ethiopia, we use the information from the United States to simulate the scenario and obtain preliminary estimates. To do that, we shock the average weight so that a reduction in number amounting to two-third of that shock leads us to the desired shift in production.

4. Results

Results of the three scenarios are presented below. Within each scenario, three cases were considered based productivity related to ideal animal health equilibrium (IAHE) level of production. We have summarized the economic surplus values from each case in **Error! Reference source not found.**. Note that all results are reported in $US.

4.1.1. Scenario 1: Increases in productivity

In response to a 25% IAHE level supply shift in productivity, live animal producers' and meat processors' surplus increases by USD 71.92 million and USD 54.51 million respectively. Live animal asset value increases by USD 694.33 million. Consumer surplus increases by USD 54.29 million.

For larger shifts of 50% and 75% of IAHE, producer surplus at farm level leads to USD 148.75 million and USD 230.47 million increase. Consumer surplus also increases by USD 110.69 million. Live animal assets value increase by USD 1.39 billion and USD 2.09 billion, respectively. In the Ideal Production State, producer surpluses at farm level and at processing level increases by USD 317.09 million and USD 234.06 million, respectively. While live animal assets increase by USD 2.80 billion.

4.1.2. Scenario 2: Shifts in consumer demand

Scenario 2 is a 15% shift in consumer demand, and the supply shifts of the same magnitude as in Scenario 1. In the case where there is a 25% IAHE level of supply shift in the live animal sector, producer surplus for live animal producers increases by USD 248.97 million while the meat processors producer surplus increases by USD 189.11 million. Consumer surplus increases by USD 143.84 million. Asset value increases by USD 935.13 million.

For productivity changes of 50% and 75% of IAHE, economic surplus in live animal production increases by USD 331.82 million and USD 419.57 million respectively. Meat processors' surplus also increases for these cases. Consumer surplus increases by USD 203.47 million and USD 265.18 million respectively. For the Ideal case, consumer surplus increases by USD 328.97 million. Total producer surplus increase by USD 891.11 million, with increased gain across the supply chain. Livestock asset value increases by USD 3.26 billion.

Table 5: Economic Surplus changes (in million USD) for selected scenarios.

Scenarios	IAHE Case[1]	Live Animal PS	Meat PS	Consumer Surplus	Asset Change
Scenario 1: Increase productivity with no change in demand	Case 1	71.92	54.51	54.29	694.33
	Case 2	148.75	111.69	110.66	1392.09
	Case 3	230.47	171.54	169.10	2093.28
	Case 4	317.09	234.06	229.62	2797.91
Scenario 2: Increase productivity with 15% shift in demand	Case 1	248.97	189.11	143.84	935.13
	Case 2	331.82	249.70	203.47	1707.48
	Case 3	419.57	312.95	265.18	2483.26
	Case 4	512.22	378.88	328.97	3262.47

[1]Case1, case2, case3 and case4 represents 25%, 50%, 75% and 100% of ideal health state respectively

4.1.3. Scenario 3: Increases in productivity, decreases in inventory size

Under Scenario 3, for each productivity case described in Scenario 1, we assume the live weight increases by 6% and inventory decreases by 4%. We explore here the distribution of gain of healthier animal rather than more animal as inventory size expected to go down, holding the output constant to scenario 1. Here, economic surpluses are similar to scenario 1 for all the agents across the supply chain as the output levels are similar. However, livestock asset values are different compared to scenario 1 as shown in Table 6. For comparison of the IAHE cases, we note that livestock asset change in this case is USD 5.93 billion, which is more than twice the value in scenario 1.

Table 6: Economic Surplus changes (in million USD) for selected scenarios.

Scenarios	IAHE Case[1]	Asset Change
Scenario 1: Increase productivity with no change in demand	Case 1	694.33
	Case 2	1392.09
	Case 3	2093.28
	Case 4	2797.91
Scenario 3: Increase productivity, decrease inventory	Case 1	1100.28
	Case 2	2455.46
	Case 3	4065.56
	Case 4	5930.56

[1]Case1, case2, case3 and case4 represents 25%, 50%, 75% and 100% of ideal health state respectively

5. Discussion

Improvements in animal health increase economic surplus for producers and consumers across all scenarios. Asset values of the livestock also moves towards positive changes. Total net surplus is positive across all scenarios, while wealth distribution is heterogeneous across economic agents and scenarios.

More specific observations are in order. First, under Scenario 1, positive increases in live animal productivity increases total production at the farm level. It also decreases price. Producer surplus estimates indicate that those at the farm level are better off, both in terms of surplus and asset changes. We note that, under this scenario there is no tradeoff between the inventory of breeding animals N and average meat production per animal. Under Scenario 2, we see that a 15% increase in consumer demand increases surpluses for all producers and consumers. Meanwhile, under

Scenario 3, if the increase in live animal productivity is offset by a decrease in the number of animals in the breeding herd, then live animal producers are predominately better off.

It is important to note that, these results are based on the assumption that the processors are able to adjust to changes in increased supply from live animal sector. In essence, they can accommodate changes due to improved animal health without facing significant losses or disruption to their business operations. Government intervention might be needed in order to keep the costs of processing the increased supply of live animals down. Infrastructural development, including accessible abattoir inspection services as well as financial aid such as lower cost loans to meat processing industry might be helpful to cut down unnecessary costs in this sector.

In summary, based on the simulations from the model for small ruminants in Ethiopia, improvements in animal health improve economic surplus for live animal producers, meat processors and consumers. Considering the expected demand increase further increase economic surpluses of all the agents. Live animal producers realize increases asset values from increases in price and/or more inventory. Evidence suggests that increasing productivity balanced with decreased inventories may be an opportunity to improve economic welfare for all economic agents in the model.

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Appendix A

Let us focus on the processors' supply equation which is defined as

$$Q_s = f^s(A) \quad \text{(A.1)}$$

Here Q_s is the supply of processed meat, which is a function of liveweight supplied by domestic and foreign producers, net off exports, A. Since, increase in the total liveweight, increases processed meat supply, so we have interior solution, i.e., $\frac{\partial f^S}{\partial A} > 0$. Processing farm's demand for inputs is given by

$$P_A = P_r \cdot f_A^s(A) \quad \text{(A.2)}$$

Here P_r is the price of meat and $f_A^s(.)$ is the marginal productivity of live animal. Supply of processed meat in linearized form is given as:

$$EQ_s = \chi_A EA \quad \text{(A.3)}$$

Where $\boldsymbol{\chi_A}$ is the cost share of liveweight in the processors' production function. Live animal inverse demand in the processing industry is given as:

$$EP_A = EP_r - \frac{1 - \chi_A}{\sigma_A} EA \quad \text{(A.4)}$$

where σ_A is the own price elasticity of substitution (Sumner & Wohlgenant, 1985). To channel the productivity improvement in the live animal sector, the value of χ_A needs to be high, which means that the meat processors do not face exponential price increase to accommodate increased supply from the farms. At the same time the, the value of σ_A needs to be lower which is indicative of high elasticity of meat processors. Meat processors with high elasticity are flexible to efficiently respond to market changes caused by animal health improvement.