An Evaluation of Livestock Health on Production Inefficiency in Western Kenya

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1 Introduction

Common issues constraining growth across underdeveloped countries are impoverished environments, food insecurity, and poor health. The World Health Organization's top three Sustainable Development Goals (SDGs) [1] of ending all forms of poverty, ending hunger through food security and sustainable agriculture, and ensuring health and promoting well-being evidence the importance placed on addressing these issues.

Sub-Saharan Africa experienced the highest worldwide poverty rate of 40.2% in 2018 [2]. While this rate has declined from 57% in 1990, population growth in Africa has resulted in an increase of more than 100 million people living in extreme poverty [3]. Energy availability in eastern sub-Saharan Africa is the lowest worldwide with less than 2500 kilocalories per person per day compared to western, developed countries having energy availability of greater than 3500 kilocalories per person per day [4]. Stunting is associated with malnutrition and negatively affects child development and life-long health [5]. The proportion of stunted children in Africa is 39%, compared to the worldwide proportion of 21.9% [6]. It is projected that the global population of extreme poor will be concentrated in Africa [3], which compounds the related issues of food security and health.

Typical social protection programs focus on interventions that reduce poverty and manage market risk as an indirect way of increasing food security [7], and thus health. Increasing household income or household production, which acts to increase income or consumption, alleviates income and food poverty. Market risk is reduced by interventions that seek income or production stabilization.

Smallholder farming systems characterize agricultural systems in rural African regions where household production, consumption, and income are closely related. Near-subsistence levels of agricultural production in smallholder farming systems have been evaluated to determine contributions to national growth and household income in developing countries. While interventions focused on the growth of non-agricultural sectors are important for development, there exists quantitative evidence that allocating a proportion of public funds to agricultural interventions in excess of agriculture's proportion of GDP can increase incomes of the poorest 2.5 more times than that of income sourced from non-agricultural sectors on average [8]. Approximately 59% of the sub-Saharan African population is engaged in smallholder, agricultural development, which has realized a 12.7% growth in livestock production from 2004 to 2014 [9], with the majority of households in farming areas keeping at least one livestock species [10]. Household livestock production is both an important income-generating activity and a means of supplying household food items [11]. Interventions that promote and then protect food security by a household reaching a level of self-reliance and sustainability through income and production are a main focus of social programs. Increasing food security is then closely followed by increased health and wellness. The high proportion of households involved in agricultural development, along with the growth in livestock production, provide natural areas to concentrate social program interventions and can help achieve the SDGs.

Interventions in school-age children to provide animal sourced foods for consumption have been shown to increase physical and cognitive development [12]. Moreover, a positive association between increased child height gain, a predictor of health [5,13,14], and livestock-owning households [15] shows a relationship between household livestock production and consumption of animal sourced foods, either through income generation or household consumption of production. It is speculated that livestock disease acts as a barrier to the consumption of animal sourced foods [15], potentially having a negative effect on health outcomes.

The production of animal sourced foods in rural, smallholder farming systems contributes both to subsistence needs and local market supply given the existence of markets. Livestock production also contributes to and is an important part of household income [16]. One of the factors acting as a constraint on the productivity of livestock production is livestock disease [10, 17]. Infectious disease outbreaks in cattle systems commonly result in decreased production of milk and weight, reproduction issues, and increased mortality [18]. Livestock mortality also occurs in severe cases of disease within pastoralist communities [10], which can be interpreted as total production loss. Consumption of animal sourced foods relies on availability through production, providing the link between livestock health and consumption availability. Decreased reproductive rates compounds availability issues by reducing future production, with mortality negatively affecting production efficiency. However, availability of food items differs from a household's ability to access food items in a market environment where purchase is necessary. Previous research has shown that increased costs of macronutrient consumption are associated with livestock illness events [19]. Livestock health not only affects availability of food items but also affects how costly it is to consume the macronutrients that make up food items even when foods items are available. Livestock health is an important factor when evaluating issues surrounding production and consumption in smallholder farming systems, and in the larger context, an important avenue to consider when constructing interventions that promote food security.

It becomes a natural extension from previous studies looking at the effects of livestock disease on a child's production of height [20], and evaluating the effects of human health on agricultural production inefficiency [21, 22], to evaluate the effects of livestock disease on livestock production directly [17, 23–25].

The objective of this paper is to provide empirical evidence on the effect livestock health has on household production specific to smallholder farming systems in rural, Western Kenya.

Using household level data spanning ten villages within this region we accomplish the objective by estimating household livestock production inefficiency and then estimate livestock health parameters that reveal probabilistic relationships with production. We extend the analysis by also estimating the effect livestock health has on the prosperity of a livestock-producing household. By accomplishing this objective we further close the gap in knowledge between livestock disease and consumption, as it relates to household production and prosperity.

Specifically, this research contributes information supporting construction of interventions that help achieve the SDGs due to its unique access to household-level data in an area of major focus. In general, this research contributes to health and development fields focused on income and food security in areas with smallholder farming systems, and the animal health economics field by taking a parametric efficiency approach instead of a non-parametric [26] or cost analysis approach [24, 25]. The topic of animal disease burden is also advanced by providing estimates that quantitatively reveal disease burden through loss in household prosperity. These results directly extend to smallholder farming systems in underdeveloped areas representative of our study area in western Kenya, which can help guide construction of interventions in other areas.

This paper proceeds as follows. In the methodology section we detail modeling approaches for estimating livestock production inefficiency and then the impact of livestock health on production inefficiency. Then we explain data used for model estimation. In the following section we report model results, interpretation, and estimated quantities of interest. We conclude with a discussion of results, implications, and direction for future research.

2 Methodology

2.1 Stochastic Frontier Analysis

Production theory and the empirical estimation of production parameters consistent with theory is widely studied across economics, business, and management fields. Measuring production efficiency is an important aspect of production analysis for informing policy [27] at the macro level, as well as informing production decisions at the micro level. The transformation, or production function relates a set of goods used as inputs to a good considered as an output. The production frontier represents the maximum number of output goods attainable using a given set of input goods [28] and provides an area of measurement for which production outcomes fall on and within. Efficiency is measured as the deviation of a particular production outcome from the frontier, with outcomes on the frontier considered as fully efficient production. Production inefficiency is measured as the distance between the frontier and a production outcome.

Analysis of production efficiency is supported by deterministic and stochastic methods. Data envelopment analysis uses linear programming methods to obtain a frontier of efficient production from decision-making units [29,30], while stochastic frontier analysis models inefficiency in an econometric framework that evaluates a specified production function's random error term [31]. While both modeling approaches offer insight on production efficiency, computation through data envelopment analysis relies only on input and output observations, which results in efficiency values absorbing any heterogeneous effects across decision-making units [32, 33]. However, the nonparametric approach of data envelopment analysis makes it flexible and widely applied under appropriate assumptions. We employ an parametric analysis of total livestock production inefficiency using stochastic frontier methods [32,34] in order to capture heterogeneity and random effects across our sample [33]. We consider total livestock production as the aggregate of production across household livestock species. We specify heterogeneous effects across villages as shifting livestock production and the mean of production inefficiency. We specify random effects across villages and livestock treatment expense, which we use to instrument unobserved variability in the availability of and means to acquire livestock medical care when health issues are present. See the Supplementary Materials section for stochastic frontier model details, derivation, and parameter estimation.

2.2 Binomial-Logistic Normal Approximation

We define a representative household as that with average livestock production inefficiency and evaluate the impacts of livestock health on production using a normal approximation to a binomial-logistic model in a Bayesian environment. A generalized linear model approach is taken because the relationship between livestock health observations and the conditional expectation of average inefficiency given livestock health is not normal or linear with certainty [35]. This modeling approach allows us to evaluate a household's odds of production becoming more or less inefficient during livestock health events. Inefficiency values are specified as 0 for those below average inefficiency and 1 for those above average inefficiency. This specification effectively creates a reference point for average livestock production inefficiency within our sample that takes into account inefficiency attributed to latent environmental effects unobserved by our data. The odds impacts of livestock health on production inefficiency are modeled in such a way that general production inefficiency from the environment is taken as given, permitting the evaluation of impacts attributed to livestock health. This environment is in contrast to typical production environments found in developed, commercialized markets, which are designed to optimize production efficiency. Production oversight and regulatory measures in developed markets also ensure best-practice and livestock welfare-improving actions are either encouraged or followed, which improves efficiency as well. Due to resource constraints and reduced regulatory capacity, increased levels of general inefficiency is inherent in underdeveloped markets.

The benefits of normally approximating a binomial generalized linear model with a normal likelihood revolve around parameter inference consistent with inference on normal random variables instead of sampling-based methods [35] due to parameters having a normal posterior distribution. We let our sample drive posterior sampling by specifying a noninformative flat prior on independent and identically distributed parameters. Incorporating prior information on parameters is made possible by augmenting a data matrix used for estimation with this information [35], but we have not seen relevant literature that informs our beliefs. The logistic link with a linear function relating livestock health to binary inefficiency values provides odds impacts interpretation from log-odds parameter estimates after exponentiation.

Controlling for village-level inefficiency effects, the highest level of household education, and communal grazing practices in the estimation of livestock health odds parameters, we estimate associated probabilities of a household having more inefficient production than the reference point when experiencing livestock illness events. The probabilities are compared to a benchmark probability of having more inefficient production when no livestock illness events occur, but still capturing unobserved general inefficiency not attributed to livestock health. The estimated probabilities are used to construct expected livestock production, which is then compared to a counterfactual estimate of fully-efficient production using expected inefficiency and observed livestock production information. Impacts on household prosperity attributed to livestock illness events are estimated using information on expected livestock output during illness events, fully-efficient production, and sample information on expected livestock unit revenue. See the Supplementary Materials section for normally-approximated binomial-logistic model details, parameter estimation, and inference, as well as information on the estimation of livestock health event probabilities and prosperity impacts.

3 Data

The data used for this paper is sourced from an ongoing population-based animal syndromic surveillance (PBASS) system used to monitor animal health in livestock producing households in Western Kenya. The PBASS system is conducted within a Health and Development

Surveillance System, overseen by the Kenya Medical Research Institute. In addition to animal health data, household demographic, asset, and consumption data are collected in a socioeconomic survey (SES PBASS). Our sample longitudinally follows randomly selected households across 10 villages from February 2013 to July 2016. See Thumbi et al. (2015) for more details on household selection and data collection methods.

Household livestock production data consists of 6,328 observations on the number of cattle, goats, sheep, and chickens sold or consumed, the number of eggs produced, and the amount of cow and goat milk produced. In production theory and evaluation of production inputs, factors of production broadly classify inputs as land, labor, and capital. We specify inputs into household total livestock production as the total number of acres between owned and rented land, the total number of household members greater than the age of three years, the total amount of income earned between off-farm activities and livestock production, and total expense between production and livestock treatment. Table 1 provides summary statistics for household total livestock production and inputs into production. On average, a household in our sample produces approximately 4 livestock units monthly and has access to two-thirds of an acre of land for production. Household labor consists of approximately four members contributing to livestock production with a maximum of 15 members and a minimum of one member. Because labor does not consist of members less than three years of age, total household members above this age acts as an upper bound on labor available due to the potential of some members allocating their time to child-raising activities. Average monthly capital consists of 3,298 Kenyan shillings (Ksh) sourced from income activities and 97 Ksh worth of investment into production and livestock health.

Table 1: Livestock Production Summary Statistics

	Livestock Production Units	Total Acres	Total HH Members	Off-Farm Income	Livestock Income	Production Expense	Treatment Expense
mean	4.28	0.67	4.06	3166.23	131.32	78.72	18.38
std. dev	2.81	0.55	2.07	6728.50	356.75	202.36	61.20
min	0.15	0	1	0	0	0	0
max	12	2	15	30000	2100	1200	300

Note: Summary statistics are presented for livestock production output and input variables consisting of land, labor, capital, and expense. Income and expense values are in Kenyan shillings (108.85 Ksh = 1 USD as of October 2020). N = 6328.

Animal disease syndrome data in PBASS consists of health observations on cattle, goats, sheep, and chickens. Animal health syndromes fall in the broad categories of reproductive, respiratory, digestive, urogenital, musculoskeletal, skin, nervous, and udder disorders. Common livestock diseases negatively effecting livestock production in Kenya consist of foot and mouth disease, East Coast fever, contagious bovine pleuropneumonia, lumpy skin disease, and malignant catarrhal fever [18]. In order to capture household livestock symptoms related to common Kenyan livestock diseases, we interact observations declaring respiratory and skin disorders whose clinical signs of cough, nasal discharge, dyspnea, hair loss, lumps, and itching correspond to symptoms related to the common diseases. The animal disease syndrome data also consists of observations of general illness, which is considered as signs of illness unrelated to categorized disorders, like respiratory or skin, and is not directly attributable to known diseases by livestock health observers. Because increases in livestock disease transmission risk is associated with communal grazing practices [36, 37], we condition livestock health observations on production with non-communal and communal grazing methods. Table 2 provides summary statistics for 398 observations on livestock health after being matched on unique household identification numbers for those households within the production data sample. This subset of production data is used as the sample estimating livestock health impacts on production inefficiency due to livestock health observations being available for production-sample households.

Table 2: Variable Summary Statistics

	General Illness	Respiratory-Skin Disorder	Communal Grazing General Illness	Communal Grazing Respiratory-Skin	No Education	Untreated
proportion	0.47	0.31	0.38	0.23	0.02	0.92
count	188	124	151	90	9	366

Note: Proportion and count summary statistics are presented for livestock health symptom presentation, communal grazing symptom presentation, household education status, and livestock treatments. Respiratory-skin disorders takes into account presentation of symptoms consistent with common livestock diseases in Kenya (FMD, ECF, CBPP, MCF). N = 398.

Almost half of the households in our sample produced livestock that experienced general illness symptoms. Slightly more than one third of households participating in communal grazing have livestock that experienced general illness symptoms. Slightly less than one third of households have livestock that presented with respiratory or skin disorders, with slightly less than one quarter of households having livestock with these presentations participating in communal grazing. Defined as the highest level of household member education, approximately 2% of households in the livestock health sample have no formal education. Households having formal education have members who have primary or secondary school experience. We choose to focus estimates on households with no formal education as a way to evaluate livestock health impacts on households considered most vulnerable. Targeting social programs across a population, those members considered less vulnerable implicitly place a lower bound on the magnitude of a program's effect, while those considered most vulnerable will realize a larger magnitude of effect. Approximately, only 1 out of 10 households in our sample treated livestock when presenting with health issues. Approximately 56% of households in the livestock health sample have production inefficiency values greater than the inefficiency reference point.

4 Results and Discussion

4.1 Stochastic Frontier Results

The ratio between deviation in production uncertainty attributed to inefficiency, σ_u, and uncertainty attributed to household-specific effects, σ_v, is defined as $\lambda = \sigma_u/\sigma_v$.The ratio λ captures the proportion of inefficiency in household-specific effects for deviations in production and $\sigma = (\sigma_u^2 + \sigma_v^2)^{1/2}$ captures total deviation in production [32, 38]. Table 3 presents livestock production parameter estimates for comparison between the unbiased and consistent ordinary least squares model, and the more efficient heterogeneous and random effects maximum likelihood models. Production function parameter estimates for inputs and village identifier are important insofar as showing reliability across production modeling and are not central to our production analysis [32, 33]. The parameters (σ, λ) are central a central focus and provide information on the contribution of inefficiency to production deviation. We see that production deviation with random effects across treatment expense and villages is almost equally attributed to deviations in inefficiency and household-specific effects with a ratio value of approximately 1. However, production deviation with heterogeneous effects in the production function and the distribution of inefficiency is attributed almost entirely to deviation in household-specific effects with a ratio of approximately 0.005.

Table 3: Maximum Likelihood Estimation of Production Function Parameters

	OLS	Distribution Hetero	Random
const	2.961102	2.971470	2.960986
total_acres	0.339416	0.339415	0.339642
labor	0.16588	0.165869	0.166243
off_farm_income	8e-06	0.000008	0.000064
livestock_income	0.0013	0.001300	0.003529
livestock_expense	0.001029	0.001029	0.004338
livestock_treat_expense	0.002574	0.002574	0.002414
vil68	-0.113206	-0.113203	-0.113245
vil55	0.260405	0.260415	0.260362
vil10	-0.077447	-0.077440	-0.077485
vil28	0.208621	0.208633	0.208486
vil53	0.036292	0.036306	0.036172
vil13	-0.12749	-0.127487	-0.127447
vil35	0.298173	0.298189	0.298136
vil49	0.188553	0.188568	0.188553
vil67	0.269668	0.269686	0.269660
σ	2.71099	2.711022	2.711093
λ	-	0.004786	0.999842

Note: Maximum likelihood estimates for SFA production function. Columns relate to ordinary least squares, heterogeneity in production and in inefficiency distribution, and random effects in the inefficiency distribution. Heterogeneity is modeled across villages and random effects are modeled across livestock treatment expense and villages. N = 6328.

Table 4 presents summary statistics for estimated distributions of production deviation attributed to inefficiency and inefficiency rates. Mean inefficiency rates for the heterogeneous and random effects model are 0.065 and 0.78, respectively, with a maximum rate of 0.131

for the heterogeneous model and 0.941 for the random effects model. The narrow interval for estimated inefficiency in the heterogeneous model is not surprising given its small value of λ.

Table 4: Stochastic Frontier Analysis Livestock Production Inefficiency

	Output Deviation		Inefficiency Rate	
	Distribution Hetero	Random	Distribution Hetero	Random
mean	3.048	1.396	0.065	0.780
sd	0.161	0.653	0.049	0.103
min	2.833	0.371	0.000	0.000
max	3.259	6.338	0.131	0.941

Note: Deviations from production and inefficiency rates are presented for livestock production models specified in the stochastic frontier analysis.

Underestimating the inefficiency component of production deviation in the heterogeneous specification is a possible drawback due to village indicators containing both heterogeneity and inefficiency, and is inherent in the modeling problem [33]. Model comparison between heterogeneous and random effects specification is not straightforward due to the central focus being the conditional error term component $E[u_i|\,\varepsilon_i]$ [33]. It is noted that the likelihood value for the random effects model (16874) is greater than the likelihood value for the heterogeneous model (15290), lending the idea that our sample is more likely to come from a random effects data generating process. Likelihood ratio testing is not applicable due to there being no parameter restrictions for specifying critical value degrees of freedom [32], and the evaluation of parameter efficiency in the null hypothesis for a Hausman specification test is also not applicable [33]. The difference in modeling revolves around the estimated distributions of inefficiency in production deviation. Because the random effects model allows estimation of inefficiency directly attributed to the household [31], the evaluation of livestock health impacts on production inefficiency proceeds with the random effects model.

4.2 Binomial-Logistic Normal Approximation Results

Linking the inefficiency reference point to livestock health through the logistic function provides log-odds parameter interpretation. Livestock health parameters greater than 0 are interpreted as increasing the log-odds of production inefficiency being greater than the reference point at its average, while parameters less than 0 are interpreted as decreasing the log-odds of being greater than the reference point. More interpretable are the odds estimates after exponentiation of log-odds parameters. Odds parameters are interpreted as increasing or decreasing the odds of production inefficiency being greater than the reference point by a factor equal to the parameter estimate, with factors greater than 1 increasing the odds and factors less than 1 decreasing the odds. Table 5 provides log-odds parameter estimates and 90% confidence intervals for the normally distributed parameters.

Table 5: Estimated Log-Odds of Being Above Mean Household Livestock Production Inefficiency

	Coefficient	Bounds	
	Log-Odds	Lower	Upper
const	0.4569	0.4176	0.4961
gen_illness	0.1423	0.1102	0.1744
respskin	0.2029	0.1689	0.2369
gen_ill_noedu	0.5905	0.4547	0.7262
respskin_noedu	0.1257	0.0199	0.2315
comgraz_genill	-0.1176	-0.1514	-0.0837
comgraz_respskin	-0.1596	-0.1983	-0.1209
untreated	0.0171	-0.0154	0.0497
vil68	-0.1259	-0.1680	-0.0837
vil55	0.0720	0.0400	0.1040
vil10	0.2035	0.1634	0.2435
vil28	0.2521	0.2031	0.3012
vil53	0.0368	-0.0002	0.0738
vil13	0.0758	0.0399	0.1116
vil35	-0.2328	-0.2698	-0.1957
vil49	0.0580	0.0239	0.0921

Note: Parameter estimates of increasing (>0) or decreasing (<0) the likelihood of household livestock production inefficiency being above representative inefficiency. Significant parameters at the .1 level have intervals that do not contain 0.

Livestock illness is significantly associated with increased odds of greater than average production inefficiencies when households do not use or have access to communal grazing land. Livestock general illness events are associated with an increase in inefficiency odds by 15.3%, with respiratory or skin disorder events having an associated increase in the odds by 22.%5. An increase of 81.1% in inefficiency odds is associated with households having no formal education during livestock general illness events. Use of communal grazing land when livestock present with general illness is associated with 11.1% decrease in inefficiency odds. A 14.7% decrease in inefficiency odds is associated with households using communal grazing land when respiratory or skin disorder events occur. Untreated symptomatic livestock is estimated to have an insignificant impact on increasing inefficiency odds. While reported, parameters for village indicators are only used to estimate subsequent probability and burden outcomes.

4.3 Household Prosperity Results

Predicted probabilities of households having more inefficient livestock production than the reference point are presented in Table 6. At the aggregate level, predicted probabilities represent the average of village-specific probabilities. Also presented in Table 6 are the expected production and production value losses associated with inefficiency and the burden of loss attributed to decreased livestock health. Loss values are the difference between the counterfactual, fully-efficient production outcome and the expected outcome under inefficiency events. The burden of decreased livestock health on production and its value is the difference between a benchmark inefficiency outcome when no livestock health events exist and the expected outcome during decreased livestock health events. Production loss estimates measure livestock unit losses attributed to a particular event, while value estimates measure livestock income lost to production impacts of particular events. The benchmark probability of inefficient livestock production can be thought of as capturing unobserved market, household, and environmental factors affecting inefficient production outcomes, which lends itself to the idea of greater general production inefficiency in underdeveloped areas compared to commercialized markets. The value of livestock health burden on production represents a lower bound for burden on total production value as livestock treatment expense is costly for households and can be mitigated against when livestock are healthy. The deviation between benchmark production and expected livestock health losses, and benchmark value loss and expected livestock health losses is focused on the distribution of predicted probability values of realizing greater production inefficiency, not the distribution of inefficiency values within the production frontier. We see that decreased livestock health is associated with rightward shifts in the distribution of inefficiency probabilities. This shift in probabilities is then mapped to rightward shifts in expected production and value losses attributed to decreased livestock health and provides broad estimates of the effects of livestock morbidity.

Table 6: Expected Burden of Decreased Livestock Health on Production and Prosperity

		Production		Value (Ksh)	
	Pr(I > R_u)	Expected Loss	Health Burden	Expected Loss	Health Burden
benchmark	0.622	3.41 (3.32, 3.53)	-	89.52 (87.03, 92.98)	-
gen_ill	0.654	3.44 (3.34, 3.57)	0.03 (-0.06, 0.15)	90.25 (87.58, 93.66)	0.73 (-1.76, 4.19)
respskin	0.668	3.44 (3.33, 3.58)	0.03 (-0.06, 0.15)	90.63 (87.99, 93.62)	1.11 (-1.38, 4.57)
gen_ill_noedu	0.773	3.53 (3.43, 3.64)	0.12 (0.03, 0.24)	92.60 (89.72, 95.65)	3.08 (0.59, 6.54)
respskin_noedu	0.695	3.47 (3.36, 3.61)	0.06 (-0.03, 0.18)	90.88 (87.98, 94.28)	1.36 (-1.13, 4.82)
comgraz_genill	0.627	3.42 (3.32, 3.55)	0.01 (-0.08, 0.13)	89.53 (86.93, 92.83)	0.01 (-2.48, 3.47)
comgraz_respskin	0.632	3.42 (3.32, 3.55)	0.01 (-0.08, 0.13)	89.94 (87.13, 93.42)	0.42 (2.07, 3.88)

Note: Expected livestock production outcomes represent burden associated with latent environmental effects and burden associated with decreased livestock health. Latent environmental effects represent the benchmark outcome. Burden values are compared to the counterfactual, fully-efficient livestock production. Value loss is measured as Kenyan Shillings. The first column represents predicted probabilities of being above the inefficiency reference point R_u. Decreased livestock health burden on production and value is measured as the decrease in livestock production units and value associated with livestock health events. Values in parenthesis represent the 50% empirical interval for burden estimates (between the 25th and 75th percentiles).

4.4 Discussion

Livestock illness event parameters for our sample support previous research evaluating the impacts of decreased livestock health on production [10, 17, 18] and provide empirical measurements of associated increases in odds of inefficient production. Cost evaluation of livestock health impacts on production provides monetary measurements of illness burden on profits, or if at the household level, income. With much of household production in small-farming or subsistence environments being consumed within the household, cost burden may not reflect livestock health impact on consumption. Household production relates inefficiency to consumption through its direct relationship consumption. The increase in inefficiency odds can be interpreted as a measurement of the burden of livestock illness on consumption. These measurements supports speculation in previous research that livestock illness is associated with decreased consumption of animal sourced foods [15], as it takes into account all food groups of consumption.

Households having no formal education during livestock general illness events is associated with the largest increase in odds of production being more inefficient than the inefficiency reference point. The associated response of production inefficiency to the interaction between general illness and education level captures the effects of managing general illness in production with varying levels of human capital. The means to acquire resources that help prevent illness or treat illness in production are made more available with increases in human capital. Within the sample used for estimating livestock health impacts, households with no formal education earn on average 2.22 Ksh in total monthly income, with households having primary school experience earning on average 2,461.43 Ksh, and households having secondary school experience earning on average 2,957.16 Ksh. Our sample shows large differences in total income between households with no formal education and those having formal education. While we cannot say that the increase in inefficiency odds is fully attributed to having no formal education in response to general illness events, the synergy between general illness and no formal education is associated with households having the largest increases in odds of more inefficient production. It is our speculation that human capital and subsequent resources are used in ways that better prevent and respond to livestock illness events, which positively impacts production efficiency. The associated impact of no formal education and respiratory or skin disorders on increasing inefficiency odds is not as great as the odds of increasing inefficiency when having no formal education and general illness events. However, the synergy and speculation still applies when thinking about the effect of less human capital and decreased livestock health.

Communal grazing increases household livestock production resources. Land and water resources not available at the household become available at the community level for livestock production when communal grazing opportunities exist. Production inefficiency decreases in environments where necessary inputs into production are available, the most basics of which in livestock production being feed and water. As communal grazing provides access to feed and water, decreased production inefficiency is expected. Parameter estimates including communal grazing components show decreased odds of greater production inefficiency even with livestock having decreased health. Pathways explaining this result center on the relationship between nutrition and health. Either the nutrition made available from communal grazing provides energy needed for adequate immune response to illnesses, or the gains in production from available nutrition absorb losses in production from decreased health. Our estimates show that while livestock health is important in production, having access to production resources is also important.

Economic prosperity is positively correlated with production outcomes for livestock producing households. The largest loss in production value is attributed to livestock general illness events when household members have no formal education. The expected monthly livestock health burden on households in this scenario is 3.08 Ksh. Average monthly total livestock income in a close neighborhood around the inefficiency reference point ($\mu_I \pm 0.005$) is 64 Ksh. The livestock health burden represents an approximate loss of 4.8% in household prosperity derived from livestock production. The three pillars of food security are described as availability, access, and utilization [39]. The loss in livestock production attributed to decreased livestock health negatively effects availability of nutrients for consumption. The direct effects center on households engaged in livestock product subsistence farming. The indirect effects center on households who source consumption through local markets, where household livestock producers form the supply chain. Access to nutrients is determined by the ability to acquire food items in market environments where food items are available for purchase. The loss in production value attributed to decreased animal health for those households selling some or all of their production negatively affects their ability to purchase food items not produced at home.

5 Conclusion

This paper has called attention to the impact livestock health has on production in household, or smallholder farming production systems found in underdeveloped areas. We provide empirical measurements of the associated increase in odds of greater livestock production inefficiency when decreased livestock health events occur. We also estimate the loss in economic prosperity attributed to decreased livestock health by comparing an expected production value outcome to production value in an environment with healthy livestock and full production efficiency. We have found that livestock general illness events and livestock having respiratory or skin disorders is significantly associated with increasing the odds of production being more inefficient. The increase in odds of greater production inefficiency is larger when households experience decreased livestock health events with members having no formal education. While the effect of greater resource availability for production in communal grazing systems absorbs negative effects from decreased livestock health, expected production outcomes during decreased livestock health events show slight losses for production units and value of production.

Social programs addressing poverty, food insecurity, and human health have developed interventions that increase household income and household production. Stability in income and production helps to manage market risks in consumption, indirectly increasing food security. One such market risk is supply risk due to shocks from livestock disease events. Interventions focused on increasing livestock health have the same indirect effects of increasing food security through increased production and economic prosperity pathways.

We have focused on the burden of animal disease at the household level and have provided one of many ways to evaluate this burden. Future research on this topic will benefit by focusing on regional or country level impacts of animal disease. Determining how animal disease impacts country-level trade systems will provide limits on growth, and thus population welfare, for agriculturally-dominant producing countries. Animal disease events found to negatively impact trade will provide areas for focused attention when constructing interventions seeking to decrease poverty and food insecurity, and improve health. Interventions in these areas of focus will also help achieve the Sustainable Development Goals.

6 Supplementary Materials

Stochastic Frontier Analysis

Stochastic frontier analysis models the observed deviations from production [32]. The deviations come from production inefficiency and household-specific effects. Livestock production y_i from a set of inputs $\mathbf{x}_i = (x_{i1}, ..., x_{ik})$ is characterized as

$$y_i \leq f(\mathbf{x}_i; \boldsymbol{\beta}),$$

with livestock production representing the aggregate number of production units for each household observation.

Inefficiency is characterized by the random component u_i with household-specific effects characterized by the random component v_i. The random inefficiency component enters production as $y_i = f(\mathbf{x}_i; \boldsymbol{\beta}) - u_i$, where $u_i \geq 0$ due to an observed output being no greater than the production function. Both production deviations formally enter the production function as

$$y = f(\mathbf{x}; \boldsymbol{\beta}) + v - u$$
$$\Rightarrow f(\mathbf{x}; \boldsymbol{\beta}) + \varepsilon.$$

The household-specific effect v_i is normally distributed with $v_i \sim \mathcal{N}(0, \sigma_v^2)$. The inefficiency term u_i follows a truncated normal distribution with truncation at 0, providing a skewed normal density for $\varepsilon_i = v_i - u_i$. The resulting log-likelihood is characterized as [32, 38]

$$\sum_{i=1}^{n} lnL(\varepsilon_i|\boldsymbol{\beta}, \lambda, \sigma) = \sum_{i=1}^{n} \left[-ln\sigma + \left(\frac{1}{2}\right) ln\frac{2}{\pi} - \frac{1}{2}\left(\frac{\varepsilon_i}{\sigma}\right)^2 + ln\Phi\left(\frac{-\varepsilon_i \lambda}{\sigma}\right) \right],$$

where $\lambda = \sigma_u/\sigma_v$, $\sigma = (\sigma_u^2 + \sigma_v^2)^{1/2}$, and Φ represents the standard normal distribution function. Gradient search methods are used to find the MLEs for $\{\boldsymbol{\beta}, \lambda, \sigma\}$. Starting values for $\{\boldsymbol{\beta}, \sigma\}$ are provided from ordinary least squares results (OLS) of $\boldsymbol{\beta} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y}$. The starting value for λ is user-chosen as 1 so as to not introduce bias in the proportional effects of production deviation. λ is interpreted as the ratio of deviation in production inefficiency to the deviation in household-specific effects. The parameter of interest is the inefficiency term u_i in $\varepsilon_i = v_i - u_i$. The empirical distribution of u_i is generated through the transformation

$$E[u_i|\varepsilon_i] = \frac{\sigma\lambda}{1+\lambda^2}\left[\frac{\phi(z_i)}{1-\Phi(z_i)} - z_i\right],$$

where $z_i = \varepsilon_i\lambda/\sigma$ and ϕ represents the standard normal density function [34]. Gauss-Markov theorem assumptions still hold even though the distribution of ε_i is asymmetric. OLS parameter estimates are still unbiased and consistent, thus being efficient linear estimates. However, MLE estimates are efficient among both linear and nonlinear classes [32].

Modeling extensions of z_i and of the production function itself allow for fixed heterogeneous effects and random effects estimation. Fixed heterogeneous effects can be specified to shift the production function and/or shift the distribution of inefficiency u_i. Shifting the inefficiency distribution is accomplished by altering z_i in the conditional expectation of u_i so that $z_i^* = z_i - \mu_i/(\sigma\lambda)$ with μ_i representing the linear combination of heterogeneous effects and parameters $\boldsymbol{\gamma}_i\mathbf{H}_i$ [33]. A random effects model is specified with the inclusion of a random parameter w_i in the production of output y_i so that $y_i = w_i + f(\mathbf{x}_i; \boldsymbol{\beta}_i) + \varepsilon_i$. It is assumed that $w_i \sim \mathcal{N}(\boldsymbol{\gamma}_i\mathbf{H}_i, \sigma_w^2)$, with $\hat{\sigma}_w^2 = Var[\hat{\boldsymbol{\gamma}}_i\mathbf{H}_i]$. Monte Carlo approximation of $\boldsymbol{\beta}$ is used in the random effects routine [31] for log-likelihood values by sampling w_i and then averaging the resulting chain of log-likelihood values for each gradient search iteration. Heterogeneous effects are captured across villages and random effects are captured across both villages and livestock treatment expense.

Normal Approximation to the Binomial-Logistic Model

A reference inefficiency point $R_u = n^{-1}\sum_{i=1}^{n} u_i$ is created for modeling livestock health impacts on production inefficiency for a representative household in our sample. To fully specify the transformed response variable for the binomial-logistic model we define $r_i = 1$ if $u_i > R_u$ and $r_i = 0$ otherwise. It is assumed that the independent and identically distributed r_i follows a binomial distribution $r_i \sim \text{Bin}(p_i)$ with $p_i \in (0, 1)$ denoting the probability of realizing an outcome r_i. The predictor η_i is used to link a $(1 \times k)$ vector of explanatory variables $\mathbf{x}_i$ to r_i through a $(k \times 1)$ vector of coefficients $\boldsymbol{\beta}$ and is assumed to be linear in $\boldsymbol{\beta}$. The log-likelihood becomes

$$
\begin{aligned}
l(r_i|p_i) &= r_i \text{log}(p_i) + (n - r_i)\text{log}(1 - p_i) \\
&\Rightarrow r_i \text{log}\left(\frac{p_i}{1 - p_i}\right) + n\text{log}(1 - p_i).
\end{aligned}
$$

With the linear predictor $\eta_i = \mathbf{x}_i\boldsymbol{\beta}$, the logistic link becomes $p_i = e^{\eta_i}/(1 + e^{\eta_i})$, further characterizing the log-likelihood as

$$
\begin{aligned}
l(r_i|\eta_i) &= r_i\eta_i - r_i\text{log}(1 + e^{\eta_i}) - n\text{log}(1 + e^{\eta_i}) + r_i\text{log}(1 + e^{\eta_i}) \\
&\Rightarrow r_i\eta_i - n\text{log}(1 + e^{\eta_i}).
\end{aligned}
$$

Following Gelman et al. (2014) the posterior distribution is computed through a normal approximation to the likelihood $L(r_i|\eta_i)$ in $\boldsymbol{\beta}$ by generating pseudodata h_i from $\mathcal{N}(h_i|\eta_i, \sigma_i^2)$. If prior information on $\boldsymbol{\beta}$ is confidently known it can be incorporated using numerical prior methods that append the vector $(0, ..., 1, ..., 0)$ to the data matrix $\mathbf{X}$, where 1 denotes the jth position in k corresponding to β_j for which the information is known. The information on β_j is directly included in the response vector $\mathbf{r}$ by including it in the $n + 1$ position. The appended value is informed by the center of the prior distribution on β_j for

$$
f(\beta_j; \beta_{j0}, \sigma^2_{\beta_j}) \propto -\frac{1}{2\sigma^2_{\beta_j}} \left(\beta_j - \beta_{j0}\right)^2 .
$$

Including prior information on all $\boldsymbol{\beta}$ is accomplished in the same fashion, extending from

n to $n+k$ observations. A diffuse prior on $\boldsymbol{\beta}$ leaves the data matrix $\mathbf{X}$ and the response vector $\mathbf{r}$ unchanged.The normal approximation is accomplished by an expansion around η_i with psuedodata taking the form

$$h_i = \eta_i - \frac{L'(r_i|\hat{\eta}_i)}{L''(r_i|\hat{\eta}_i)}$$
$$\sigma_i^2 = -\frac{1}{L''(r_i|\hat{\eta}_i)}.$$

Differentiating the log-likehood provides

$$\frac{\partial l}{\partial \hat{\eta}_i} = r_i - n\frac{e^{\hat{\eta}_i}}{1+e^{\hat{\eta}_i}}$$
$$\frac{\partial^2 l}{\partial \hat{\eta}_i^2} = -n\frac{e^{\hat{\eta}_i}}{(1+e^{\hat{\eta}_i})^2},$$

completely characterizing pseudodata as

$$h_i = \eta_i + \frac{(1+\hat{\eta}_i)^2}{e^{\hat{\eta}_i}}\left(\frac{r_i}{n} - \frac{e^{\hat{\eta}_i}}{1+\hat{\eta}_i}\right)$$
$$\sigma_i^2 = \frac{1}{n}\frac{(1+\hat{\eta}_i)^2}{e^{\hat{\eta}_i}}.$$

The normal approximation proceeds by generating $\mathbf{h} = (h_1, ..., h_n)^T$ and then approximating the likelihood $L(r_i|p_i)$ through a weighted linear regression of explanatory variables $\mathbf{X}$ on $\mathbf{h}$ using $(\sigma_1^2, ..., \sigma_n^2)$. The center of the normal approximation is provided by iteratively altering η_i through $\boldsymbol{\beta}$. The center $\hat{\eta} = \mathbf{X}\hat{\boldsymbol{\beta}}$ is provided by the choice of $\hat{\boldsymbol{\beta}}$ that satisfies the convergence criterion, and thus achieves the posterior mode. Inference on β_j is directly made through the posterior distribution $\beta_j|\mathbf{r} \propto \mathcal{N}\left(\beta_j|\hat{\beta}_j, (\mathbf{X}^T\text{diag}(-L''(\mathbf{r}|\hat{\eta}))\mathbf{X})_{jj}^{-1}\right)$. Livestock health event probabilities are estimated with the invariance principle $\hat{p} = e^{\hat{\eta}}/(1+e^{\hat{\eta}})$.

The evaluation of livestock health impacts on inefficiency is extended to evaluating impacts on production output and value of production. Mean livestock health event probabilities computed across villages characterize expected output. For a given livestock health event with probability p being above the inefficiency reference point R_u, output y, inefficiency I, expected output is calculated as

$$E[y] = p(y \mid I > R_u) + (1 - p)(y \mid I < R_u).$$

An empirical distribution of expected production output is created through Monte Carlo simulation. 50% credible intervals for the 25th and 75th percentiles are computed using the resulting empirical distribution of expected values.

Computing a representative livestock output value under fully efficient production provides a reference point to compare actual, inefficient production. Expected production value loss from livestock health events is computed by taking the difference between representative livestock output and expected livestock output under decreased health events, and multiplying the difference by representative livestock income per unit. Fully efficient representative livestock output is characterized as $y_{\text{eff}} = \left(n^{-1} \sum_{i=1}^{n} y_i\right)(1 + R_u)$. For observed livestock income m_i, representative livestock income per unit is characterized as $m_{\text{inc}} = \left(n^{-1} \sum_{i=1}^{m} m_i\right) / \left(n^{-1} \sum_{i=1}^{n} y_i\right)$. The expected impact of livestock health events on production value is estimated as $W = m_{\text{inc}}\left(y_{\text{eff}} - E[y]\right)$. 50% credible intervals for the empirical distributions of W are computed using the 25th and 75th percentiles.

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