

## DEVELOPMENTAL ECONOMICS

## Livestock vaccinations translate into increased human capital and school attendance by girls

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To fulfill the United Nation's Sustainable Development Goals (SDGs), it is useful to understand whether and how specific agricultural interventions improve human health, educational opportunity, and food security. In sub-Saharan Africa, 75% of the population is engaged in small-scale farming, and 80% of these households keep livestock, which represent a critical asset and provide protection against economic shock. For the 50 million pastoralists, livestock play an even greater role. Livestock productivity for pastoralist households is constrained by multiple factors, including infectious disease. East Coast fever, a tick-borne protozoal disease, is the leading cause of calf mortality in large regions of eastern and Southern Africa. We examined pastoralist decisions to adopt vaccination against East Coast fever and the economic outcomes of adoption. Our estimation strategy provides an integrated model of adoption and impact that includes direct effects of vaccination on livestock health and productivity outcomes, as well as indirect effects on household expenditures, such as child education, food, and health care. On the basis of a cross-sectional study of Kenyan pastoralist households, we found that vaccination provides significant net income benefits from reduction in livestock mortality, increased milk production, and savings by reducing antibiotic and acaricide treatments. Households directed the increased income resulting from East Coast fever vaccination into childhood education and food purchase. These indirect effects of livestock vaccination provide a positive impact on rural, livestock-dependent families, contributing to poverty alleviation at the household level and more broadly to achieving SDGs.

## INTRODUCTION

The Sustainable Development Goals (SDGs) set targets for poverty reduction and the consequent impact of poverty on education, health, and human opportunity (1). Despite notable gains in relation to some SDG targets, Africa continues to have the highest rates of persistent poverty and food insecurity in the world (2). In sub-Saharan Africa, more than half of the population is engaged in small-scale farming (3). The majority of households in the farming sector keep one or more livestock species, which not only represent wealth, income, and protection against economic shock but also are a major source of high-protein nutrition, which is critically important in a continent where childhood stunting remains prevalent (4, 5). For the more than 50 million African pastoralists for whom livestock raising is the primary economic activity, livestock play an even greater role in economic and food security (6).

Livestock productivity for pastoralist households is constrained by multiple factors, including infectious disease. A longitudinal examination of indigenous zebu cattle during the first year of life in Kenya revealed an all-cause mortality rate of 16.1 (13.0 to 19.2; 95% confidence interval) per 100 calf years (7). Using a Cox proportional hazard model, East Coast fever (ECF) resulting from infection with *Theileria parva* was identified as the main cause of death, responsible for 40% of all mortality within the first year (7). Mortality due to ECF is preventable by vaccination, with efficacy demonstrated both in experimental challenge trials and in field trials with natural exposure (8). Given the high impact of ECF on cattle and the importance of cattle as financial assets and insurance instruments for the economic and food security of pastoralists, we developed econometric models of the ECF vaccine adoption decision to estimate both direct effects of vaccine adoption on livestock health and productivity and

indirect effects on household expenditures that are directed toward specific SDG goals, including education, food, and health.

We present findings from pastoralist households centered on their decision to vaccinate (or not to vaccinate) against ECF and the impacts of that decision on household welfare. In doing so, we present a novel framework that extends beyond the direct animal health and productivity effects typically measured from a livestock-centric viewpoint to more fully capture the human development benefits of vaccination against a highly prevalent livestock disease. This framework provides an evidence base for emphasizing broader household decisions and their role on the impact of interventions, such as vaccination delivery. In doing so, we demonstrate the importance of using econometric analysis at the household level for tracking how economic gains are directed toward human welfare improvement and for meeting broad social goals, such as the SDGs.

## RESULTS

Results from ECF vaccine adoption are reported first, followed by impacts on antibiotic and acaricide use, livestock productivity and value, and household expenditures, including those for food, health, and education. Tables S1 and S2 present variable definitions and descriptive statistics.

## ECF vaccine adoption

We examine the factors that influenced household decisions to vaccinate calves, 1- to 2-year-old cattle (that is, heifers and bullocks), and adult cattle (>2 years) in the past 12 months. Vaccination costs matter in theory for the adoption decisions, but because there is little or no variation in vaccination costs reported by households, they were excluded as a regressor. Three explanatory variables are consistently associated with the decision to vaccinate across all age categories. First, the current number of owned livestock is associated with significantly greater vaccination uptake across all age categories (Table 1,  $P < 0.01$ ). Second, the fraction of crossbred cattle, which produce higher quantities

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**Table 1. Determinants of ECF vaccine adoption.**

	Number of vaccinated adult cattle	Number of vaccinated 1- to 2-year-old cattle	Number of vaccinated calves
Number of cattle <sup>†</sup>	0.235***	0.375***	0.562***
Fraction of exotic breed <sup>†</sup>	0.490***	0.443***	0.665***
Expected milk loss due to ECF <sup>†</sup>	0.111***	0.044	0.043*
Vaccine information source: Nongovernmental organization <sup>‡</sup>	0.086*	0.051	0.022
Vaccine information source: Farmers <sup>‡</sup>	0.014	0.061	0.106**
Service provider: Community animal health worker <sup>‡</sup>	-0.375***	0.028	-0.019
Service provider: Veterinary supply shop <sup>‡</sup>	-0.144***	-0.091**	-0.147*
Intercept term	0.971	-0.079	-0.578
Number of observations	356	356	356
R <sup>2</sup> , pseudo-R <sup>2</sup>	0.44	0.42	0.50

\* $P = 0.1$  (level of significance).  
 †Elasticities (continuous regressors).  
 ‡Percent change (binary regressors).

\*\* $P = 0.05$  (level of significance).

\*\*\* $P = 0.01$  (level of significance).

†Elasticities (continuous regressors). ‡Percent change (binary regressors).

of milk than indigenous breeds but are more susceptible to severe disease and death upon ECF infection, is positively related to vaccination across all age groups (Table 1). Third, when animal health services are obtained from a commercial vendor, there is a significantly lower vaccination rate (Table 1), an effect that is not observed when vaccine information is obtained from either other farmers or nongovernmental organizations. The herd owner's expectation of the impact of ECF infection on milk production is statistically significant and positive for the number of adult cattle and calves that are vaccinated (9, 10) (Table 1; full regression results are presented in models S0 to S3 in table S3).

### Impacts on antibiotic and acaricide use

In the absence of vaccination, ECF infections can be treated with antibiotics to reduce severe morbidity and mortality. ECF infections can be reduced by periodic treatment of livestock with acaricides to kill the tick vector before transmission (98% of households reported routinely applying acaricides). Consequently, we examined whether vaccination against ECF decreases subsequent use of antibiotics and acaricides. The instrumental variables used to control for endogeneity are the predicted numbers of vaccinated cattle from regressions in Table 1. The effect of a 1% increase in vaccination, conditional on herd size, significantly reduced overall antibiotic use by 0.11% for 1- to 2-year-old cattle ( $P < 0.01$ ). The marginal effect of vaccinations for 1- to 2-year-old cattle is 0.30 (on the basis of the elasticity estimate 0.11), which implies that 10 vaccinations for this age group reduce subsequent antibiotic use by an average of about three treatments per year, holding herd size constant. Multiplying the marginal effect by the average number of cattle in the cohort provides antibiotic treatment reductions of 1.89 for an average herd's 1- to 2-year-old cattle. On the basis of an estimated cost per treatment of 1110 Kenyan shillings (Ksh), this provides cost savings of 2105 Ksh per year. The estimated cost per treatment of 1110 Ksh is the average cost from respondents in the survey, which is consistent with a previously reported cost of 1000 Ksh per treatment (11). These cost savings do not account for labor and time costs

of antibiotic treatment and are thus an underestimate of total antibiotic treatment cost savings. Full regression results for antibiotic use are provided as model S4 in table S3.

For households who vaccinate for ECF, immunized cattle receive 0.29 fewer acaricide applications per month than do unvaccinated cattle, which corresponds to an average of 3.46 fewer treatments per year for a vaccinated animal. Given an estimated cost per application of 6 Ksh, this provides a savings of about 21 Ksh per vaccination per year. This savings does not account for additional savings through reduction of labor for application. The reduction of acaricide applications may indirectly amplify the impact of ECF vaccine adoption at the herd level because decreased acaricide use has been shown to allow infection with nonpathogenic *Theileria* species that provide at least partial protection against ECF due to *T. parva* (12). Alternatively, the reduction of acaricide use may result in an increase in other tick-borne diseases, which would likely reduce the net savings from less frequent acaricide use.

### Direct impacts on livestock productivity and value

Households in the survey produced milk, consumed it at home, and sold it but rarely purchased it. Severe ECF disease results in marked loss of milk production in cows and can progress to death in cattle of all ages. A 1% increase in the fraction of vaccinated adults is associated with a statistically significant 0.08% increase in mean reported milk production per herd (Table 2). On the basis of sample means, milk production is about 0.13 liters higher per adult animal with one additional adult vaccination. For the average adult cohort size, vaccination provides about 0.27 liters per day per herd on average (66 adult cattle  $\times$  0.13/31 days), or about 96.6 liters per year. At 45 Ksh/liter, this amounts to a savings of 4347 Ksh per year. This average milk production improvement is conditional on several factors, including incidence of ECF infection, proportion of crossbred cattle in the herd, proportion of lactating cows in the herd, and herd management practices. Where incidence is higher, ECF burden on milk production will be greater and, correspondingly, lesser where incidence is lower, so the

**Table 2. Impact of ECF vaccination on milk production and prevention of mortality.**

	Average milk (liters) per cow	Total ECF attributable deaths	Adult ECF attributable deaths	1- to 2-year-old ECF attributable deaths	Calves ECF attributable deaths
Fraction of vaccinated adults <sup>†</sup>	0.080***				
Number of vaccinated cattle <sup>†‡</sup>		-0.056*			
Number of cattle <sup>†</sup>		0.239***			
Number of vaccinated adults <sup>†‡</sup>			0.010		
Number of adult cattle <sup>†</sup>			0.089		
Number of vaccinated 1- to 2-year-old cattle <sup>†‡</sup>				0.004	
Number of 1- to 2-year-old cattle <sup>†</sup>				0.148**	
Number of vaccinated calves <sup>†‡</sup>					-0.086***
Number of calves <sup>†</sup>					0.228***
Fraction of exotic breed <sup>†</sup>	0.187***	-0.173***	-0.265**	-0.153*	-0.118*
Grazing management <sup>§</sup>	0.092**	0.093*	0.068	0.198***	-0.003
Intercept term	-0.190	1.089***	0.495	-0.197	-0.378
Number of observations	386	349	351	352	352
R <sup>2</sup> , pseudo-R <sup>2</sup>	0.42	0.09	0.05	0.08	0.08

\* $P = 0.1$  (level of significance). \*\* $P = 0.05$  (level of significance). \*\*\* $P = 0.01$  (level of significance). †Elasticities (continuous regressors). ‡Predicted value. §Percent change (binary regressors).

estimate can be interpreted as the weighted average of disease burden over the entire sample. Both the fraction of crossbred cattle in the herd and more intensive grazing management practices have a significant and positive impact on average milk offtake per cow (Table 2).

A higher vaccination rate is associated with fewer ECF deaths for calves and for the herd as a whole (Table 2). The calf vaccination effect, represented by an estimated elasticity of  $-0.086$  ( $P < 0.01$ ), is the largest source of whole-herd death reduction; the vaccination effect for all cattle ( $-0.056$ ) exhibits a smaller effect in magnitude as compared to calves but remains statistically significant at the 10% level. This age effect is consistent with the incidence of ECF transmission during the first year of life (7). For calves, the estimated elasticity implies a marginal effect of 0.033, which means that for every 100 calves that are vaccinated, 3.3 calves are saved from ECF death (1 for each 30 vaccinations). The average value of a calf based on a market survey within the study region is approximately 10,000 Ksh. Multiplying the calf death reduction of 0.033 by the value of a calf provides expected savings of 330 Ksh per calf vaccination. As with milk production savings, savings from prevented mortality is conditional on the overall incidence of ECF within the region and would be higher where ECF burden is greater and lesser where ECF burden is lower. Table S4 provides results for the full set of analyzed relationships.

### Indirect impacts on expenditures in health, education, and food

To this point, we have reported the direct impacts of vaccination on cattle productivity and animal health inputs, but economic theory suggests the potential for broader impacts on household decisions and outcomes. Cattle death from ECF results in less asset wealth in the

form of livestock for a household. This in turn reduces a household's capacity to translate livestock wealth into disposable income for consumable or marketable meat and milk for current consumption or investment in other capital, such as human health and education. Although households who vaccinate may also have a higher propensity for consumption and investment in general, the instrumental variable estimation strategy as applied here controls for this propensity and thereby alleviates bias and inconsistency in parameter estimates. Table S5 provides the full set of analyzed variables.

ECF vaccinations are positively associated with education expenditures (Table 3). At the mean household level, a 10% increase in the number of vaccinated cattle (holding herd size constant) results in a 0.88% increase in education expenditures. The mean educational expenditure across all households in the study is 44,260 Ksh, implying that, on average, 406 Ksh more is spent on education for each additional vaccination. To further understand the consequence of this finding, we examine the distribution of elasticities across households. We find that for a 10% increase in the number of vaccinated cattle, the 5% most responsive households (exhibiting the largest elasticities) would increase their education expenditures by 5.4%. The 10, 50, and 90% most responsive households increase their education expenditure by 3.5, 1.2, and 0.7%, respectively. In terms of gender, attendance in secondary school by girls is positively associated with ECF vaccination rates (that is, fewer cattle deaths); for boys, attendance in both primary and secondary schools is negatively associated with the number of ECF deaths (see table S6).

There is a statistically significant effect (at the 1% level) of ECF vaccinations on food (meat, beans, rice, and maize) consumption expenditures (Table 3). A 10% increase in the number of vaccinated cattle resulted in a

**Table 3. Parameter estimates for expenditures on education, human health, and food.**

	Education expenditure	Human health expenditure	Food expenditure
Number of vaccinated cattle <sup>†‡</sup>	0.088**	0.042	0.056***
Household size <sup>†</sup>	0.701***	0.351***	0.326***
Off-farm income, ≤5000 KSh <sup>§</sup>	Base case		
Off-farm income, 5000–10,000 KSh <sup>§</sup>	0.091	0.044	−0.083
Off-farm income, 10,000–20,000 KSh <sup>§</sup>	0.498***	0.456***	0.182*
Off-farm income, 20,000–40,000 KSh <sup>§</sup>	0.549*	0.573**	0.108
Off-farm income, 40,000–80,000 KSh <sup>§</sup>	0.707**	0.350*	0.204***
Off-farm income, >80,000 KSh <sup>§</sup>	1.005***	0.707**	0.145
Intercept term	1.916***	0.823***	0.184**
Number of observations	346	350	346
R <sup>2</sup> , pseudo-R <sup>2</sup>	0.26	0.15	0.27

\* $P = 0.1$  (level of significance). \*\* $P = 0.05$  (level of significance). \*\*\* $P = 0.01$  (level of significance). †Elasticities (continuous regressors). ‡Predicted value. §Coefficients (binary regressors).

0.56% increase in food expenditures. Given that the sample mean food expenditure is 2701 Ksh per week, 16 Ksh more is spent on average for food per week per vaccination (for a total of about 151 Ksh per week).

Given that ECF is not a zoonotic disease, no expenditures are required for prevention or treatment of ECF infections in humans. However, reductions in income and wealth due to cattle death loss may still, in principle, affect human health outcomes through effects on household capacity to invest in health maintenance and treatment of illness. Yet, we find no statistically significant impact of the number of ECF vaccinations on human health expenditures, though we do see significant effects of off-farm income on health expenditures (Table 3). To the extent that human health expenditures are often unforeseen income shocks, the finding that ECF vaccination (as an instrument for on-farm income) does not affect human health expenditures is corroborated by findings of past research (13).

## DISCUSSION

This study uses a household econometric model to evaluate both the direct and indirect impacts of the pastoralists' decision to vaccinate (or not to vaccinate) cattle against ECF. Adoption of ECF vaccination by pastoralists benefits household welfare through four primary direct effects: (i) prevention of ECF-associated cattle deaths, which occur predominantly in the first year of life and represent an asset loss; (ii) prevention of ECF-associated decreases in milk production; (iii) reduction in expenditures for antibiotics needed to treat ECF infections; and (iv) reduction in expenditures for chemical acaricides that are used to limit tick infestations. The economic model provides a framework for estimating the indirect effects of ECF vaccination on household expenditures directed toward relevant SDG goals, such as food, health, and education.

The net benefit of ECF vaccination is 3580 Ksh for the average household of 15 people with a mean herd size of 66 mature cattle

[the sum of avoided death loss, milk loss, and antibiotic and acaricide treatments less the cost of vaccination (650 Ksh per head)]. Relative to SDG goals, the largest impact of ECF vaccination is on educational expenditures: an average increase of 3895 Ksh over a 4-month period, or 406 Ksh per vaccination. The top 5% of households increased their education expenditures by 5.4% for each 10% increase in proportion of cattle that were vaccinated. Education is the single largest expense across households with a high propensity to change, and it has a significant impact on the likelihood of male and female children attending school. There were also significant household expenditures on food (excluding milk) of 151 Ksh per week (2420 Ksh per 4 months). Results suggest that on-farm income, which indirectly reflects the impact of ECF vaccination, and off-farm income are an important basis for funding education and food, whereas off-farm income is an important basis for health care expenditures. Differences in the liquidity of these sources of income may be a reason for their distinct roles. Education expenditures are more easily planned for, because they tend to come regularly at the beginning of school terms, whereas many health care expenditures are less easily planned for and may come as emergencies. In the bigger picture, the empirical evidence supports the idea that economic growth and human capital accumulation reinforce one another (14). Education leads to growth, and growth, in turn, raises the demand for education. Consequently, policies or interventions that increase household wealth will also lead families to further educate their children, thereby increasing wealth in the succeeding generation (14).

Given our findings that vaccinating cattle for ECF increases economic wealth for pastoralist households and that this economic wealth translates into additional expenditures on education and food, understanding the determinants of household adoption is important for maximizing benefits at a community and regional level. Consistent themes are evident across the decisions to adopt the ECF vaccine. The likelihood of vaccine adoption and the number of cattle vaccinated per household are both positively influenced by the number of cattle

owned by the household, the fraction of crossbred cattle in the herd, and the household's expected milk loss from ECF infection. The latter two determinants are strongly interrelated because crossbred cattle, incorporating European genetic determinants, produce more milk than indigenous breeds but are also more susceptible to severe disease, resulting in cessation of milk production and/or death. This indicates that pastoralists who have a higher investment in their herds, both in number and in adding higher productivity traits, are the most likely to vaccinate. In effect, they are mitigating asset and income risk with vaccination. Our data do not identify when vaccination was introduced relative to expansion of herd size and breed improvement. However, prevention of death losses, especially in European breeds and European/indigenous crossbred animals, would likely promote both expansion and genetic improvement. Notably, the likelihood of vaccine adoption and the number of cattle vaccinated per household are higher when health information is reportedly received primarily from other pastoralists. This is consistent with technology adoption studies in agricultural development (15) and, more recently, with the impact of social networks and media on individual vaccination decisions and parental decisions to vaccinate children (16–18). In contrast, the likelihood of vaccine adoption is negatively correlated to information and services from animal health professionals and/or local commercial providers of veterinary products. This may reflect a specific disincentive for product providers to recommend vaccination if they recognize the potential impact of vaccinations on antibiotic and acaricide sales.

The current ECF vaccine is far from ideal: It requires a continuous cold chain, it is expensive relative to other livestock vaccines, and, as a live vaccine, it can itself induce severe disease, requiring post-vaccination antibiotic use (8). These characteristics may be a disincentive for both commercial providers (because of the requirement for cold storage) and pastoralists (because of cost and availability). Consequently, development of an improved ECF vaccine may markedly amplify the direct and indirect impacts observed with the current vaccine.

The reduction in the use of both antibiotics and acaricides following adoption of vaccination suggests broader societal benefits beyond household welfare. Development of antibiotic-resistant bacteria is a global concern, and the use of antibiotics in livestock contributes to the emergence and maintenance of resistant bacteria, reducing the effectiveness of antibiotics for both human and animal diseases (19). Similarly, intensive use of chemical acaricides that include compounds toxic to humans in the absence of strict regulation results in environmental contamination and increased concentration in water sources during dry seasons. The reduced use of antibiotics and acaricides when ECF vaccination is adopted supports the need for increased adoption of existing livestock vaccines and development of new ones, including an improved ECF vaccine.

This study highlights the centrality of household decisions in understanding the key determinants of technology adoption and in tracking how economic gains from adoption are directed toward broader goals. In the absence of a household-centered approach, which, by definition, reflects familial priorities and decision-making, livestock vaccination and childhood education may be viewed as being unrelated. However, by integrating household priorities for both income generation and expenditure, the connection becomes evident. It is an important step in addressing the imperfect ability to assess the impacts of animal disease control (20). Understanding these linkages allows integrated efforts across disciplines to effectively form policy and achieve ambitious targets, such as the United Nation's SDGs.

## MATERIALS AND METHODS

We summarized the economic theory, data, and econometric strategies that were used in this analysis. Additional details are provided as Supplementary Materials.

### Economic model of household production and consumption

Agricultural household models are widely used in microeconomic research on development (21–23) and provide guidance for modeling ECF vaccine adoption decisions and estimating the impact on household economic outcomes. These models characterize household production relationships and decisions, consumption opportunities and preferences that together drive consumption decisions, and decisions at the interface between production and consumption. The value of household production includes both the explicit value of goods that are produced and sold on the market and the implicit value of goods that are produced and consumed within the same household. Likewise, household consumption “expenditures” include the value of both purchased and self-produced goods that are consumed, because in-home consumption entails forgoing income from market sales (22). By allocating time and resources to household production and consumption of the goods that it produces, the household implicitly buys time and goods at their opportunity cost (the market wage) from itself.

Households act as if they maximize their income (including both market and in-home production value) and then choose their consumption decisions on the basis of this income. If a production input or technology sufficiently increases profitability of the household production enterprise, then it will tend to be adopted, likely with ancillary production adjustments. Consequently, household income will rise with profitability, which allows increased expenditures on basic goods, such as food, durable goods, and investments in human capital, such as schooling and health.

The structure of the household economic model provides a theoretical foundation for econometric regression estimation and hypothesis testing. In particular, it provides a foundation for specifying and testing the following: (i) input decisions, such as ECF vaccine adoption and antibiotic use, as a function of household characteristics; (ii) household productivity as a function of management decisions and current asset structure; and (iii) effects of assets, income, and management on household consumption and investment expenditures.

### Household survey and data

The survey questionnaire that was used for data collection targeted variables that were hypothesized to represent the most important and quantitatively accessible determinants of ECF vaccination decisions, ECF-related livestock health, and productivity outcomes, and important household consumption categories that may change because of the economic impacts of vaccination. The survey instrument was designed, piloted, and fielded according to standard statistical and econometric approaches (24). Informed consent by each household was obtained after the nature and consequences of the study were explained. A two-stage sample design was followed, first selecting clusters and then households, with selected groups of households more intensively sampled than others to facilitate analysis (24). Survey responses were voluntary. Local enumerators first received training and then were supervised over the course of the survey.

The sample was constructed to be representative of the region with sufficient heterogeneity in household, livestock, and geography to provide variation in important livestock management practices and outcomes vis-à-vis ECF. For the analysis, households were categorized

into four subregions within southern Kenya: District 1, Kajiado and Isinya (43.7% of households); District 2, Narok (43.3%); District 3, Transmara (7.0%); and District 4, all other (northernmost) districts (6.0%). District 4 is nearer Nairobi, with more intensive management for milk production and less pasture exposure (and hence less exposure to ticks). District 3 is in southwestern Kenya, which is more rural and remote. ECF vaccination is used in only about 40% of herds in our sample and sparse across herds and almost always incomplete within herds. For example, on average, only 16% of the adult cattle were reported to be vaccinated.

### Econometric estimation

Econometric estimation of adoption decisions, productivity outcomes, and household expenditure effects is pursued through regression analysis, the details of which are determined jointly by the structure of available data and supporting economic theory. Model estimation is complicated by two factors: regressor endogeneity and limited-distribution-dependent variables. Endogeneity of regressors can lead to biased and inconsistent estimated effects if not accounted for (25). We accounted for endogeneity using standard two-stage estimation methods as described in the Supplementary Materials. In addition, many of our dependent variables (regressands) took the form of non-normal conditional distributions or contained count data. We used variable transformations, limited dependent variable regressions, and count regression models as described in the Supplementary Materials.

### SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/2/12/e1601410/DC1>

Supplementary Text

table S1. Descriptions of variables used in analysis.

table S2. Summary statistics for variables used in the regressions.

table S3. Determinants of ECF vaccine adoption and antibiotic treatment.

table S4. Impact of ECF vaccination on milk production and prevention of mortality.

table S5. Parameter estimates for expenditures on education, human health, and food.

table S6. Poisson regression models of children in school correlated with ECF deaths or vaccinated adult cattle.

table S7. Parameter estimates for expenditures on education, human health, and food with predicted livestock profit.

References (26, 27)

### REFERENCES AND NOTES

- The complete list of goals, targets, and indicators is available at <https://sustainabledevelopment.un.org> [accessed 14 November 2016].
- FAO, IFAD, WFP. *The State of Food Insecurity in the World, 2014. Strengthening the enabling environment for food security and nutrition* (Rome, FAO, 2014). Available at: [www.fao.org/3/a-i4037e.pdf](http://www.fao.org/3/a-i4037e.pdf) [accessed 14 November 2016].
- <http://data.worldbank.org/topic/agriculture-and-rural-development> [accessed 14 November 2016].
- R. E. Black, C. G. Victora, S. P. Walker, Z. A. Bhutta, P. Christian, M. de Onis, M. Ezzati, S. Grantham-McGregor, J. Katz, R. Martorell, R. Uauy; Maternal Child Nutrition Study Group, Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* **382**, 427–451 (2013).
- E. M. Mosites, P. M. Rabinowitz, S. M. Thumbi, J. M. Montgomery, G. H. Palmer, S. May, A. Rowhani-Rahbar, M. L. Neuhouser, J. L. Walson, The relationship between livestock ownership and child stunting in three countries in eastern Africa using national survey data. *PLOS ONE* **10**, e0136686 (2015).
- S. Krätli, C. Huelsebusch, S. Brooks, B. Kaufmann, Pastoralism: A critical asset for food security under global climate change. *Animal Front.* **3**, 42–50 (2013).
- S. M. Thumbi, M. B. Bronsvort, H. Kiara, P. G. Toye, J. Poole, M. Ndila, I. Conradie, A. Jennings, I. G. Handel, J. A. W. Coetzer, J. Steyl, O. Hanotte, M. E. J. Woolhouse, Mortality in East African shorthorn zebu cattle under one year: Predictors of infectious-disease mortality. *BMC Vet. Res.* **9**, 175 (2013).
- W. I. Morrison, D. J. McKeever, Current status of vaccine development against *Theileria* parasites. *Parasitology* **133**, S169–S187 (2006).
- A. M. Weis, The effects of expectations on technology adoption: Some empirical evidence. *J. Ind. Econ.* **42**, 341–360 (1994).
- N. Rosenberg, On technological expectations. *Econ. J.* **86**, 523–535 (1976).
- S. B. Martins, G. Di Giulio, G. Lynen, A. Peters, J. Rushton, Assessing the impact of East Coast Fever immunisation by the infection and treatment method in Tanzanian pastoralist systems. *Prev. Vet. Med.* **97**, 175–182 (2010).
- M. E. J. Woolhouse, S. M. Thumbi, A. Jennings, M. Chase-Topping, R. Callaby, H. Kiara, M. C. Oosthuizen, M. N. Mbole-Kariuki, I. Conradie, I. G. Handel, E. J. Poole, E. Njiiri, N. E. Collins, G. Murray, M. Tapio, O. T. Auguet, W. Weir, W. I. Morrison, L. E. B. Kruuk, B. M. C. Bronsvort, O. Hanotte, K. Coetzer, P. G. Toye, Co-infections determine patterns of mortality in a population exposed to parasite infection. *Sci. Adv.* **1**, e1400026 (2015).
- M. Mohanan, Causal effects of health shocks on consumption and debt: Quasi-experimental evidence from bus accident injuries. *Rev. Econ. Statistics* **95**, 673–681 (2013).
- P. Glewwe, H. G. Jacoby, Economic growth and the demand for education: Is there a wealth effect? *J. Dev. Econ.* **74**, 33–51 (2004).
- P. Bardhan, C. Udry, *Developmental Microeconomics* (Oxford University Press, 1999).
- E. K. Brunson, The impact of social networks on parents' vaccination decisions. *Pediatrics* **131**, e1397–e1404 (2013).
- R. Edge, J. Heath, B. Rowlingson, T. J. Keegan, R. Isba, Seasonal influenza vaccination amongst medical students: A social network analysis based on a cross-sectional study. *PLOS ONE* **10**, e0140085 (2015).
- V. C. Barclay, T. Smieszek, J. He, G. Cao, J. J. Rainey, H. Gao, A. Uzcianin, Positive network assortativity of influenza vaccination at a high school: Implications for outbreak risk and herd immunity. *PLOS ONE* **9**, e87042 (2014).
- M. Woolhouse, M. Ward, B. van Bunnik, J. Farrar, Antimicrobial resistance in humans, livestock and the wider environment. *Philos. Trans. R. Soc. London Ser. B* **370**, 20140083 (2015).
- B. Perry, D. Grace, The impacts of livestock diseases and their control on growth and development processes that are pro-poor. *Philos. Trans. R. Soc. London Ser. B* **364**, 2643–2655 (2009).
- J. L. Lusk, J. Roosen, J. Shogren, *The Oxford Handbook of the Economics of Food Consumption and Policy* (Oxford University Press, 2011).
- J. E. Taylor, I. Adelman, Agricultural household models: Genesis, evolution, and extensions. *Rev. Econ. Household* **1**, 33–58 (2003).
- M. Mendola, Farm household production theories: A review of institutional and behavioral responses. *Asian Dev. Rev.* **24**, 49–68 (2007).
- A. Deaton, *The Analysis of Household Surveys: A Microeconomic Approach to Development Policy* (Johns Hopkins University Press, 1997).
- W.H. Greene, *Econometric Analysis* (Prentice Hall, 2003).
- G. Feder, R. E. Just, D. Zilberman, Adoption of agricultural innovations in developing countries: A survey. *Econ. Dev. Cult. Change* **33**, 255–298 (1985).
- R. H. von Haefen, D. J. Phaneuf, Estimating preferences for outdoor recreation: A comparison of continuous and count data demand system frameworks. *J. Environ. Econ. Manag.* **45**, 612–630 (2003).

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