Relationships between livestock grazing practices, disease risk, and antimicrobial use among East African Agropastoralists

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Abstract

Livestock health is economically important for agropastoral households whose wealth is held partly as livestock. Households can invest in disease prevention and treatment, but livestock disease risk is also affected by grazing practices that result in inter-herd contact and disease transmission in regions with endemic communicable diseases. This paper examines the relationships between communal grazing and antimicrobial use in Maasai, Chagga and Arusha households in Northern Tanzania. We develop a theoretical model of the economic connection between communal grazing, disease transmission risk, risk perceptions, and antimicrobial use, and derive testable hypotheses about these connections. Regression results suggest that history of disease and communal grazing are associated with higher subjective disease risk and greater antimicrobial use. We discuss the implications of these results in light of the potential for relatively high inter-herd disease transmission rates among communal grazers and potential contributions to antimicrobial resistance due to antimicrobial use.

Introduction

Communicable livestock disease is costly for livestock-dependent households and communities in the tropics, and can be especially important for the economic well-being of low-income rural households for whom livestock represents a primary household asset. Livestock disease results in loss of wealth and income through livestock mortality and decrease in livestock productivity (Marsh et al. 2016; Lybbert et al. 2004). It also poses a threat to human health through loss of animal-based protein intake, zoonosis and food-borne illnesses (Narrod et al. 2012; Caudell et al., 2017; Mosites et al. 2015).

Livestock disease burden can be mitigated by reducing disease transmission risk, by reducing animal susceptibility, and through treatment. Disease transmission risk is dependent on general animal husbandry such as grazing and feeding practices that affect the frequency and nature of inter-herd contact (Bronsvoort et al., 2004; Rufael et al., 2008; Schoonman & Senyael Swai., 2010). Illness in the face of transmission risk can be avoided or mitigated by modern vaccination strategies, antibiotic use, traditional medicine, and other treatment methods. These targeted avoidance and treatment investments by herd owners are mediated through perceptions and understanding of disease transmission risk and the relative benefits and costs of avoidance and treatment options. Thus, general livestock husbandry and targeted disease management decisions can be related to, and through, livestock health.

In East Africa and other parts of the world, there is substantial variation in livestock feeding and grazing practices depending on localized environmental factors, land tenure, and cultural norms (Nugent and Sanchez, 1993; Davies and Hatfield, 2007). In areas with sufficient rainfall and forage availability and relatively limited grazing land, fodder is often brought to livestock and grazing is more limited (Caudell et al. 2017, Keyyu et al. 2006). In more arid environments, extensive grazing is widely practiced, and in Tanzania in particular, communal and transhumant grazing practices are common. These types of grazing practices may lead to higher rates of inter-herd contact and disease transmission than under other management practices (Bohm et al., 2009; Hutchings and Harris, 1997, Keyyu et al. 2006) such as "zero grazing" common among the Chagga and some peri-urban Arusha households (Caudell et al 2017).

Antimicrobials are an important health intervention widely used in livestock and poultry management even in remote, rural communities as a prophylaxis, as treatment for microbial and protozoal infections, and in some (primarily commercial) settings for growth augmentation (Page and Gautier 2012, Perry et al. 2013). As with other management inputs, the extent of antimicrobial use is driven in part by the perceived value of the input, and is likely to be used more where the threat and incidence of diseases thought to be treatable with antimicrobials is high (Gustafson and Bowen 1997). Antimicrobial use can also reduce the extent of pathogen shedding and the likelihood of transmission to other animals, but may also lead to development of antibiotic resistance within the microbiome.

Thus, communal grazing is potentially related to disease risk through higher rates of direct and indirect inter-herd contact than private grazing or zero-grazing. Higher objective risk may then be associated with higher perceived disease risk. Therapeutic antimicrobial use may increase in response to actual incidence of disease (and therefore disease risk), and prophylactic antimicrobial use would be positively correlated with perceived disease risk. The perceived marginal value of antimicrobials could be higher where actual or perceived risk is high, potentially leading to higher antimicrobial use.

The objective of this paper is to examine the relationships between livestock grazing practices, past disease outcomes, and demand for antimicrobials among agropastoralists of

Northern Tanzania. We develop a theoretical model that elucidates basic connections between grazing practices, past and current disease incidence, and antimicrobial use. We then estimate these relationships by using data from surveys of agricultural households around ecologically heterogeneous regions of Mount Meru and Mount Kilimanjaro. This heterogeneity in ecology leads to widely different grazing practices, from communal grazing to zero-grazing in the region, and allows us to examine how grazing patterns are related to antimicrobial use. There are some changes in the grazing patterns of the Maasai with the seasons, but the inhabitants on the slopes of Mount Meru and Mount Kilimanjaro tend to keep their animals confined, with fodder delivered to the animals. This zero-grazing behavior is relatively stable over all seasons in a year (Caudell et al. 2017).

Communal land tenure and use and transhumant grazing can provide vital benefits in spatiotemporally variable climates (Nugent and Sanchez, 1993; Agrawal, 2001; Davies and Hatfield, 2007; Ostrom, 2015). That said, overgrazing has long been recognized as a potential problem of communal grazing land ownership, although the details of the social contract over communal grazing can be important mitigating factors (Swallow and Bromley, 1995; Runge 1981; Ciriacy-Wantrup and Bishop, 1975). Additionally, communal grazing and transhumant management practices may increase disease transmission risk (Muneme et al., 2008; Maloo et al., 2001; Sanderson et al., 2000) and impose disease risk on other grazers that may not be fully accounted for in the private decision calculus of an individual herd owner. The consequence is that disease transmission mitigation practices and safeguards are likely to be under-applied, and disease transmission may be higher than socially optimal (Hennessy et al., 2005; Phillipson, 2000; Brito et al., 1991).

The historic value of antimicrobials for global health outcomes is hard to overstate (Gustafson and Bowen 1997, Kingston 2000). But antimicrobial resistance is becoming a major public health concern globally, and the use of veterinary antimicrobials in agriculture sectors may be an important contributor (Carlet et al., 2012, Van Boeckel et al. 2015). To the extent that antimicrobial use or misuse can impose external costs on other herd owners through antimicrobial resistance, herd owners may tend to overuse or misuse antimicrobials from a social economic efficiency perspective (Althouse et al., 2010), which may exacerbate the emergence and prevalence of antimicrobial resistance (Secchi and Babcock, 2002; Laximinarayan and Brown, 2001; Brown and Layton, 1996).

The externalities described above – higher potential inter-herd disease transmission from communal grazing, reduced pathogen shedding due to effective antimicrobials and reduced effectiveness from antimicrobial resistance – interact in complex ways. While our data do not allow us to tease out the externalities associated with these dimensions of grazing and antimicrobial use, we are able to examine the relationships between communal grazing, reported livestock illness, and antimicrobial use, and therefore contribute to an understanding of the incentives surrounding antimicrobial use for livestock in agropastoral settings.

We contribute to the literature in several ways. We extend the analysis of Caudell et al. (2017) who treat communal grazing as a component of Maasai ethnicity, and account for the fact that grazing decisions of households may be jointly (endogenously) determined along with antimicrobial use in response to disease risk. Moreover, we extend Caudell et al. (2017) by conceptualizing how past disease incidence contributes to current antimicrobial use, perhaps through its impact on perceived risk. In doing so, we also contribute to the literature on subjective risk assessment generally. Subjective inference about disease risk is often based on sparse information from direct observation, indirect covariates, broader belief contexts, and plays an important role in the perceived marginal value of risk-reducing management practices (MacLachlan et al., 2016; McNamara et al., 2006; Clark, 2013; Cole et al., 2003; Johnson et al., 1993; Mittal and Ross, 1998; Tversky and Kahneman, 1973). Although the role of perceptions in avoidance behavior has been well documented in economics (Courant and Porter, 1981; Crocket, Foster and Shogren, 1991; Dickie and Gerking, 1996; Ahamad, 2016), the evidence of the impact of disease risk perceptions on disease mitigation and control strategies such as vaccination and antimicrobial use is scant.

Theoretical Model

We examine how grazing patterns and past disease history relate to antimicrobial use. Grazing patterns and fodder collection practices chosen by livestock owners depend on relative forage availability, water availability, and land tenure characteristics, and other factors (Caudell et al., 2017; Pringle and Landsberg, 2004; Coppolillo, 2000).[1] While grazing practices change somewhat over grazing seasons, the basic pattern of less travel and herd interaction in higher rainfall regions versus more travel and more herd interaction with more arid conditions is a relatively stable, long-term phenomenon (Bollig, 2006). In contrast, decisions about and variation in antimicrobial use can likely be more easily altered in the short-run, depending on the real and perceived disease risk a herd owner faces. These differences allow us to divide the decision process into two stages; the communal grazing decision as a stable, quasi-fixed management practice, and antimicrobial use as a variable input with more flexibility in response to disease risk and outcomes.

[1] Formally, the Tanzanian Government owns all land in the country, but allocates use rights among villages and other private entities. Common grazing land is widely available, and pastoral land tenure in Tanzania is better described as a common property system than private property (Smith et al., 2001).

Based on this decision environment, we consider a two-stage expected profit (net income) maximization model, with stages distinguished by a long-term grazing decision and a short-term antimicrobial use decision.[2] In the first stage, the farmer chooses the proportion of the household herd to graze on common grazing land (the grazing rate). In the second stage, the farmer chooses antimicrobial use to maximize expected short-run profits based on preventive and therapeutic antimicrobial goals, the disease environment, and grazing practices. Expected profit to the household from livestock is

$$\pi = v(g;\tilde{g})\big(1-\gamma(g;\tilde{g},\tilde{a},\rho)\alpha(a;\tilde{a})\big) - ca.$$

The function $v(g;\tilde{g})$ is the potential value to a household of livestock production in the absence of disease. The household communal grazing rate is g, and communal grazing by other households is $\tilde{g}$. $v(g;\tilde{g})$ increases at a decreasing rate with the communal grazing rate g and decreases with the communal grazing rate of other households ($v_g > 0, v_{gg} < 0, v_{g\tilde{g}} < 0$, where subscripts represent partial derivatives throughout).

The term $\big(1-\gamma(g;\tilde{g},\tilde{a},\rho)\alpha(a;\tilde{a})\big)$ is the fraction of potential livestock value realized given disease losses. The function $\gamma(g;\tilde{g},\tilde{a},\rho) \in (0,1)$ is the fraction of livestock value lost to disease in the absence of private (own-herd) antimicrobial use, where ρ is the background (environmental) disease prevalence. Regional antimicrobial use by others $(\tilde{a})$ can reduce private infection risk to the herd, and communal grazing rates by others $(\tilde{g})$ can increase infection risk $\big(\gamma_g > 0, \gamma_{\tilde{g}} > 0, \gamma_{\tilde{a}} < 0, \gamma_\rho > 0\big)$. In addition, the marginal losses from grazing increase with the grazing rates of other households, and background disease prevalence $\big(\gamma_{g\tilde{g}} > 0, \gamma_{g\rho} > 0\big)$.

[2] Our focus on expected profit maximization is consistent with an assumption that herd owners are risk neutral or that there is separation between consumption and production (Singh et al. 1986, De Janvry et al. 1991, Pitt and Rosenzweig 1984). Allowing for risk-aversion would not affect the qualitative hypotheses we develop with our model.

The function $\alpha(a;\tilde{a}) \in (0,1)$ is the reduction in the loss rate from private antimicrobial use. Antimicrobial use reduces losses at a decreasing rate ($\alpha_a < 0, \alpha_{aa} > 0$), and the marginal effectiveness of a declines with regional antimicrobial use, $\tilde{a}$ due to its impact on antimicrobial resistance ($\alpha_a < 0, \alpha_{aa} > 0, \alpha_{a\tilde{a}} > 0$). Thus, regional antimicrobial use has two competing impacts: reductions in disease transmission due to its effect of reducing transmission of antimicrobial-susceptible pathogens, and increases in losses from the transmission of antimicrobial resistant pathogens.

The marginal costs of antimicrobial use is c. Additional grazing costs are suppressed for clarity. Other exogenous factors may drive the value of production, e.g., market prices, livestock characteristics, total forage usage, and other inputs, grazing impacts on disease, and antimicrobial use effectiveness. These are omitted above for clarity but discussed below as they apply to the empirical analysis.

In summary, net returns from livestock ownership are $v(1-\gamma\alpha)$ minus private antimicrobial costs ca. The function γ embodies the harm from disease and is a function of grazing and antimicrobial use. Communal grazing has two effects: it increases the value of livestock by providing food for the animals, but may decrease the value of livestock through disease morbidity and mortality. Regional and private antimicrobial use mitigates disease losses, but antimicrobial use also may reduce its effectiveness through resistance.

Expected net returns are solved by backward induction by choosing antimicrobial use subject to grazing practices, and grazing practices conditional on expected optimal antimicrobial use. The first-order condition for the second stage (antimicrobial use) decision is

$$\pi_a = -v\gamma\alpha_a - c = 0.$$

The first-order condition gives a standard result of private marginal benefit of antimicrobial use equal to marginal cost of antimicrobial use, and assuming the Implicit Function theorem holds, antimicrobial demand is $a^* = a(g, \rho, \tilde{a}, \tilde{g}, c)$. The marginal rate of substitution between a and g is

$$\frac{\partial a}{\partial g} = -\frac{\partial \pi_a / \partial g}{\partial \pi_a / \partial a} = -\frac{\alpha_a (v_g \gamma + v \gamma_g)}{v \gamma \alpha_{aa}} > 0.$$

From this relationship we have our first hypothesis:

> ***Hypothesis 1:*** *More antimicrobials are used by households that graze more on communal grazing lands.*

Optimal antimicrobial use in relation to the baseline disease risk, conditional on the grazing rate is

$$\frac{\partial a^*}{\partial \rho} = -\frac{\partial \pi_a / \partial \rho}{\partial \pi_a / \partial a} = -\frac{\gamma_\rho \alpha_a}{\gamma \alpha_{aa}} > 0,$$

implying a second hypothesis:

> ***Hypothesis 2:*** *A higher background disease prevalence is associated with higher antimicrobial use.*

The first stage first-order condition for grazing is (after applying the envelope theorem based on the first order condition for antimicrobial demand) is

$$\frac{\partial \pi}{\partial g} = v_g \, (1 - \gamma \alpha) - v \gamma_g \, \alpha = 0 \, ,$$

which indicates that the marginal value of grazing equal to the marginal cost of disease exposure due to grazing, accounting for optimal response to antimicrobial use. Communal grazing demand is $g^* = g(\rho, \tilde{a}, \tilde{g}, c)$, which includes the same arguments as a^* (except g itself).

Losses from livestock illness are represented by $l^* = v(g^*)\big(\gamma(g^*; \tilde{g}, \tilde{a}, \rho)\alpha(a^*; \tilde{a})\big)$, and dependent on (endogenous) grazing and antimicrobial use. Losses increase with increase at the margin from communal grazing by $\frac{\partial l^*}{\partial g^*} = v_g\gamma\alpha + v\gamma_g\alpha$ and decrease at the margin from antimicrobial use by $\frac{\partial l^*}{\partial a^*} = v\gamma\alpha_a$ (evaluated $g^*$and a^* in both cases).

From a social welfare perspective, private decisions about communal grazing and antimicrobial use have impacts beyond the household through $\tilde{g}$ and $\tilde{a}$. To examine the implications of these inter-household impacts, assume there are N+1 identical households as described above, and define $\tilde{g} = \sum_{j=1}^{N} g = Ng$ and $\tilde{a} = \sum_{j=1}^{N} a = Na$. In other words, the sum of other households' communal grazing and antimicrobial use increase or decrease the morbidity and mortality losses to a household. Given that $\tilde{a} = \sum_{i=1}^{N} a,$ a one unit increase in one household's use of antibiotics adds one unit to $\tilde{a}$, so the net externality of a household's antibiotic use on all N other households at the margin is

$$E_a = N\frac{\partial \pi^*}{\partial \tilde{a}} = -Nv(\alpha\gamma_{\tilde{a}} + \gamma\alpha_{\tilde{a}}),$$

where $\pi^* = \pi(\rho, c, \tilde{g}, \tilde{a})$ is the indirect profit function.[3] The net marginal external cost of antibiotic use across N identical users is $E_{\tilde{a}} = NE_a$.

The marginal externality of one household grazing on communal land due to contributions to disease incidence is similarly

$$E_g = N\frac{\partial \pi^*}{\partial \tilde{g}} = N\big(v_{\tilde{g}}(1-\gamma\alpha) - v(\alpha\gamma_{\tilde{g}} + \gamma\alpha_a a^*_{\tilde{g}})\big),$$

and the communitywide externality is $E_{\tilde{g}} = NE_g$. Note that the externality in this case has three parts: a) the negative effect on grazing productivity, b) increased transmission risk due to grazing

[3] The indirect effects through the choice variables a and g cancel out per the Envelope Theorem.

itself, and c) increased antimicrobial resistance from the induced increase in antimicrobial use in response to higher transmission and disease risk from grazing.

Data and Econometric Methods

To test hypotheses 1 and 2 above, we run regressions to represent communal grazing and demand for antimicrobials, and a third regression to estimate the relationship between grazing, antimicrobial use, and livestock illness:

$$g^* = g(c, \rho, \tilde{a}, \tilde{g}) = g(\boldsymbol{X})$$
$$a^* = a(g, c, \rho, \tilde{a}, \tilde{g}) = a(g^*, \boldsymbol{X})$$
$$l^* = l(g, c, \rho, \tilde{a}, \tilde{g}) = l(g^*, a^*, \boldsymbol{X})$$

Because the characteristics of our data define the specific estimation strategies we use, we first describe our data, and then describe our regression estimation procedures.

Data collection was performed by Washington State University, with a protocol approved by the Tanzania National Institute for Medical Research. Data were collected from 416 households in 13 villages, and the dataset is made up of one record (observation) per household (Caudell et al 2017). There are three main ethnic groups that inhabit the area of study, which ranges between Mount Meru and Mount Kilimanjaro in North Central Tanzania, and West to the Ngorogoro area (Figure 1). The Arusha and Chagga populate the slopes of Mt. Meru and Mt. Kilimanjaro, respectively, while the Maasai mostly live in the surrounding steppe. Some Arusha live in lower lying areas interspersed among Maasai to the West of Arusha Town in Monduli District. The Chagga generally live in the higher rain fed, green regions around Mount Kilimanjaro, and their herds are generally small (mean herd size = 8.9) and more confined. Maasai mostly live in the more arid lowland steppe plains. Their herds are relatively large (mean herd size = 345.5), and they mainly rely on communal grazing to feed their animals given the predominant land tenure system in Tanzania. The green regions around Mount Meru are mostly inhabited by the Arusha. Again, with greater forage around the farms, they typically rely less on communal grazing than the Maasai.

[Insert Figure 1 here]

Table 1 describes each of the variables used in the analysis, and Table 2 provides summary statistics. *Antimicrobial use* (represented by a in our theoretical model) provides information about antimicrobial inventories on-hand in each household, which are used to develop an antimicrobial use index. The index indicates the presence of syringes/needles for antimicrobial injection and number of types of antimicrobials on-hand in a household at the time of survey enumeration[4]. The largest number for any household was 7, and the lowest was 0, therefore, our index ranges from 0 to 7. As such, our antimicrobial use data are treated as count data in our analysis (refer to Figure 2). The average index value of antimicrobials on hand in a household is 1.69 (standard deviation 1.63) (Table 2). One hundred fifty-seven out of the 382 households did not have any antimicrobials/syringes in their inventory. Virtually none of the Chagga households held antimicrobials or syringes, and virtually all Maasai households held some, while Arusha households varied more in their antimicrobial holdings.

[Insert Table 1 Here]

[Insert Table 2 here]

Communal grazing (represented by g in our theoretical model) is the fraction of animals in a household's herd that are regularly grazed outside the household or compound, therefore, g ranges in the unit interval.

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[4] The inventories included four types of antibiotics (Oxytetracycline, Penicillin, Streptomycin and Sulfa and Tylosin), acaricides, anti-protozoal drugs and syringes and needles that indicated self-use. The most commonly found drug in the inventories was Oxytetracycline.

We hypothesize that background disease prevalence, measured imperfectly in our data through recent history of local livestock illness, affects antimicrobial use through its impact on herd owner risk perceptions (MacLachlan et al., 2016; McNamara et al., 2006; Clark, 2013; Pingali and Carlson, 1985; Dickie and Gerking, 1996). *Current illness* is the number of animals reported sick during the time of the survey, and is a proxy for current and expected illness outcomes (represented by $\nu\gamma\alpha$ in the model). *Prior illness* is the number of animals reported sick in the past year prior to current illnesses. Figure 2 contains histograms of *current illness, prior illness*, *antimicrobial use* and *communal grazing*.

[Insert Figure 2 Here]

Sheep/goats, and *cattle* herd size are important control variables in the analysis. They relate to total herd livestock value (*v*), and in conjunction with grazing rates determine the number of animals grazed on communal land. The Chagga and Arusha who inhabit Mt. Meru and Mt. Kilimanjaro often practice zero-grazing because the rainfall in these regions is plentiful and land is limited, while the Maasai generally use communal grazing, and live in more arid conditions. About 50% of the sample consists of Maasai households and the other 48% of the sample is made up of Chagga and Arusha. About 2% of the sample households belong to other ethnicities.

Other variables that we hypothesize may explain the differences in the *antimicrobial use* include total household *income*, *household size*, and method of consultation regarding livestock health. The household *income* variable is measured in Tanzanian Shillings (10,000s). Crop inventory, and sale were converted into monetized value, and added to the cash income to indicate total household wealth. Cash income is a good indicator of wealth for Chagga and Arusha, but Maasai may have less cash income, and more crop income. Therefore, recent sale prices of the produce were multiplied by crop stored and sold quantities to estimate cash value of the crops.

The variable *Govt. Vet.* is an indicator variable equal to 1 if household uses a professional veterinarian for livestock health consultation, and zero if household uses traditional methods or over-the-counter antimicrobials. *Distance to urban* is the natural logarithm of distance between the household and an urban center, and *Distance to market* is the logarithm of distance between the household and a market. We include these variables as proxies to control for access to antimicrobials, livestock health services, and both livestock and human population density.

Empirical Model

We developed two econometric models to test our hypotheses: (a) a model of communal grazing rates conditional on household characteristics, and (b) an instrumental variables model of antimicrobial use conditional on grazing patterns, prior livestock disease, and household characteristics. A third regression model is used to estimate the relationship between livestock illness rates, communal grazing and antimicrobial use.

A fractional Probit regression is used to model the grazing practices of the households because the dependent variable, *communal grazing* (g), is the proportion of a herd grazed bounded by zero and one (see Figure 2).[5] Following Papke and Woolridge (1996), the conditional expectation of the grazing rate is

$$E(g_i|\boldsymbol{X}_i) = \Phi(\boldsymbol{X}_i\boldsymbol{\beta}) + \eta_i,$$

where $\Phi(\boldsymbol{X})$ is a standard normal cumulative distribution function and $\boldsymbol{X}$ includes rainfall, ethnicity dummy variables and other available exogenous controls that may explain grazing

[5] Fractional probit or logit regressions are used when the dependent variable is a proportion bounded by zero and one.

patterns, and η_i is a random disturbance. The fractional Probit model is estimated via quasi-maximum likelihood using the Stata® 14 *fracreg* routine.

Antimicrobial use is count data, with a high proportion of zeros. A zero-inflated Poisson model is used for estimation using Stata® 14 *zip* routine. This specification implicitly assumes that the decision to use antibiotics is not systematically different from the decision about how much or how many antimicrobials to use. The first stage in the econometric model characterizes the probability of a household having no antimicrobials on hand ($a = 0$). Following Greene (1994); $\text{Prob}[a = 0|g, \boldsymbol{X}] = F(a|g, \boldsymbol{X})$. The probability of nonzero antimicrobials on hand is $Prob[a = j|\boldsymbol{X}, a > 0] = (1 - F(a|g, \boldsymbol{X})) = \frac{\exp(-\lambda)\lambda^j}{j!}$; where $\lambda = \lambda(g, \boldsymbol{X})$ and is the conditional mean of the Poisson process. Hence,

$$E[a|g, \boldsymbol{X}] = F * 0 + \left(1 - F(a|g, \boldsymbol{X})\right) * E[a|g, \boldsymbol{X}, a > 0] = \left(1 - F(a|g, \boldsymbol{X})\right)\lambda.$$

F is estimated as a logit such that $prob[q = 1|g, \boldsymbol{X}] = \frac{\exp(\boldsymbol{X}'\boldsymbol{\delta})}{1+\exp(\mathbf{X}'\boldsymbol{\delta})}$, which results in the following probability regression that can be estimated using maximum likelihood, motivated in Greene (1994);

$$E(q = 1|g, \boldsymbol{X}) = F_l(\boldsymbol{X}'\boldsymbol{\delta}) + \mu_l,$$

where μ_l captures producer heterogeneity. $\boldsymbol{X}$ Constitutes all the factors described in the theoretical model, and g is the grazing rate. The second stage (the Poisson process) can be estimated using the canonical formulation motivated by Cameron and Trivedi (1986),

$$\ln(\lambda_i) = \boldsymbol{X}_i'\boldsymbol{\delta} + \varepsilon_i,$$

where ε_i captures unobserved heterogeneity among households in the data sample.

Our theoretical model treats *communal grazing* (g) as a quasi-fixed choice variable and is endogenous in the intermediate run, depending on several factors including land grazing characteristics and land tenure. We therefore apply a two-stage approach to estimation of the *antimicrobial use* regression by replacing the actual value of g with the predicted values of g from a regression of grazing on a set of explanatory variables. In two-stage instrumental variable estimation, an adjustment must be made to attain consistent covariance estimates (Greene, 2011), which we perform.[6] Evidence of over-dispersion was found in the data that could be due to heterogeneity in household preferences or the nature of the process generating the excess zeros (Mullahey, 1986). The Vuong test (Vuong 1989) suggests that the excess zeros are generated by a separate process, justifying a zero-inflated Poisson regression.

A final regression estimates the relationship between current livestock illness, antimicrobial use, and grazing rates. *Current illness* is also a count variable (see Figure 2) and a Vuong test suggests that a zero-inflated Poisson regression is justified. The standard errors are again adjusted for instrumental variable use as they were in the antimicrobial regression.

Results

We present results for the grazing regression, the antimicrobial use regression, and the illness regression in turn. In the grazing regression (Table 3), the coefficient for *rainfall* is negative, large and statistically significant ($P < 0.001$), consistent with grazing intensity being higher in arid environments whereas feed and fodder is brought to livestock in the high rain fed areas and grazing is only used as an extensive margin. The coefficients for ethnicity indicators, *Arusha* and *Chagga*, are also negative relative to the Maasai; consistent with the grazing behaviors of these ethnicities.

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[6] The Maximum Likelihood covariance matrix is $\hat{\sigma}^2(\boldsymbol{Z}'\boldsymbol{X}(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}'\boldsymbol{Z})^{-1}$, where $\boldsymbol{Z}$ are potentially endogenous variables and X are exogenous. This estimate is biased because the standard second stage estimated variance $\hat{\sigma}^2 = \mathrm{n}^{-1}(\boldsymbol{y} - \widehat{\boldsymbol{Z}}\boldsymbol{\beta})'(\boldsymbol{y} - \widehat{\boldsymbol{Z}}\boldsymbol{\beta})$ are calculated using the predicted values from the first stage regressions. A consistent estimate of the σ^2 is calculated as, $\hat{\sigma}^2_{ub} = \mathrm{n}^{-1}(\boldsymbol{y} - \boldsymbol{Z}\boldsymbol{\beta})(\boldsymbol{y} - \boldsymbol{Z}\boldsymbol{\beta})'$, based on the original values of instrumented variables in $\mathbf{Z}$, and the unbiased covariance matrix is calculated using , $\hat{\sigma}^2_{ub}$, the unbiased estimate of σ^2.

These ethnic dummy variables are excluded instruments for the second stage antimicrobial regression, where ethnic grazing practices are hypothesized to be more long-term, historical phenomena shaped by environment, culture and land tenure issues, while antimicrobial use is a modern risk management phenomenon that is more fluid and not subject to these factors. Therefore, controlling for ecological factors and livestock and human densities, ethnic background is taken to affect antimicrobial use through livestock management practices like communal grazing.

Distance to Urban and *Distance to Market* are proxies for human and livestock densities and market access. Urban areas tend to be located at higher rainfall regions within our sample, and distances to markets tend to be short. Their associated coefficients are consistent with higher communal grazing rates in steppe environments that receive lower rainfall and support lower human and livestock densities.

[Insert Table 3 here]

For the antimicrobial use regression the results show a positive relationship between *communal grazing* and *antimicrobial use,* corroborating *hypothesis 1* (Table 4). The null hypothesis that *communal grazing* does not affect *antimicrobial use* is rejected at 1% level of significance ($P < 0.001$) in the logit regression, while we fail to reject the null hypothesis in the case of Poisson regression. These results suggest that, conditional on controls, *communal grazing* is associated with higher of antimicrobial use, but does not (statistically speaking) influence how many types of antimicrobials a household will use. This pattern might result if households tend to use a broad-spectrum antimicrobial (like oxytetracycline in our sample) for all disease challenges, or if they face just one or a few diseases for which one antimicrobial will suffice. Overall, a 10% increase in the *communal grazing* rate is associated with about 7% increase in *antimicrobial use* evaluated at sample means (i.e. $(\partial a/\partial g)\,/(\bar{g}/\bar{a})$). It is worth noting that *communal grazing* captures herd-contact imperfectly, and there could be other mechanisms of herd contact like watering holes and livestock transactions.

[Insert Table 4 here]

The analysis also shows a positive effect of *prior illness* on *antimicrobial use,* which is consistent with *hypothesis 2*. A unit increase in the *prior illness* number is associated with an increase in antimicrobial usage of 0.87 and the coefficient is significant at 5% level for both the Logit and Poisson regression components. This result is consistent with how reference levels and loss aversion play a role in behavior (Tversky and Kahneman, 1991; Kahneman, Knetsch and Thaler, 1991). "Availability bias" can be another reason why farmers may use more antimicrobials after experiencing salient illness events in the recent past (Tversky and Kahneman, 1973). To the extent that herd owners understand the disease risks associated with *communal grazing* and use *prior illness* as an indicator of underlying disease risk, they can affect subjective risk assessment and therefore the extent of *antimicrobial use*.

Higher household *income* is associated with higher antimicrobial adoption rates, but not the number antimicrobial types used. If household production and consumption are separable activities, if livestock husbandry is a purely financial enterprise, and if antimicrobial use is solely providing benefits in terms of reduced livestock morbidity and mortality, we might expect household income to have no effect on antimicrobial use (Marsh et al., 2016). There are several reasons why income may have an effect. First, if liquidity constraints affect the ability of households to purchase antimicrobials, then income may affect antimicrobial purchases (Carter and Yao, 2002). Second, antimicrobial use for livestock may provide human health benefits to the extent that antimicrobial use in household livestock mitigates zoonotic disease incidence.

Third, while livestock may be an important economic asset, household herds and their well-being may hold cultural significance beyond their market, income and consumption value (Quinlan et al., 2016).

Rainfall is also positively related to *antimicrobial use* given grazing practices and other controls. Higher rainfall can support taller grass, which can lead to high tick intensity in herds and may lead to higher disease transmission risk and more frequent use of antibiotics, antiprotozoans and acaricides.

The method of consultation that households use can also influence antimicrobial use. Our results show that use of *govt. vet* is associated with an intercept shift of -0.3; a lower rate of antimicrobial holding and use. Although we cannot identify underlying drivers of this result and variation in use of veterinary services is closely tied to the three primary ethnic groups identified in this study, it is consistent with professional advice acting to reduce antimicrobial use (all else constant) relative to private use by herd owners. Note, however, that the use of veterinary services an endogenous decision, likely affected by the cost of and access to professional services. Large herd owners may choose to make antimicrobial use decisions on their own depending on the fee structure of professional veterinary health care providers, and fees may be larger in rural areas relative to urban/peri-urban settings due to travel cost differences.

Distance to urban does not appear to be correlated with *antimicrobial use*. Nevertheless, *distance to market* is associated with a decrease in *antimicrobial use*, perhaps due to higher acquisition costs or, perhaps, less disease challenge through inter-herd contact.

Table 5 provides illness regression results with one regression that excludes *antimicrobial use* as a regressor (Regression 1) and one that includes an instrument for *antimicrobial use*.[7] Regression 1 shows that an increase in *communal grazing* is associated with a higher incidence of sick animals. This is consistent with *hypothesis 1*, suggesting that communal grazing may lead to higher rates of illness through higher transmission.

This first regression can be interpreted as a reduced form regression in which household demand for antimicrobials is implicit, and it is included primarily as a robustness check to compare with Regression 2.

[Insert Table 5 Here]

Regression 2 (columns 3 and 4 of Table 5) includes an instrumental variable for antimicrobial use (the predicted values from the regression in Table 4). The associated negative parameter under "No Sick Animals" indicates that the probability of having no illness is negatively associated with antimicrobial use. The positive coefficient under "Number of Sick Animals" indicates that there is a positive association between *antimicrobial use* and the number of sick animals. To relate this result back to our theoretical model, recall that the marginal effect of antimicrobial use on illness is $\frac{\partial \iota^*}{\partial a^*} = \nu\gamma\alpha_a$<0, suggesting we would expect to see a negative relationship between antimicrobial use and illness. Note, however, that our *current illness* measure is the number of current reported illnesses, and therefore better characterized as $\nu\gamma$ rather than $\nu\gamma\alpha$. As such, our available metric is an incomplete measure of illness because it does not measure the degree or duration of illness – the characteristics of illness that therapeutic antimicrobial use would most likely affect. Thus, the positive relationships between *antimicrobial use* and *current illness* in this regression is consistent with a scenario in which antimicrobial use is primarily therapeutic instead of preventive, which, based on out-of-sample

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[7] Figure 2 shows an outlier observation with reported current illness of nearly 400 animals. Both regressions in the table remained qualitatively unchanged in both parameter magnitude and statistical significance. We therefore report only the regressions based on the full sample.

anecdotal field evidence appears to be the case in most households. Conditional on grazing practices, illness frequency increases when background risk increases ($\gamma_\rho > 0$), and *hypothesis 2* is that antimicrobial demand increases with background illness risk, and so the estimated positive relationship between *antimicrobial use* and *current illness* is likely picking up this signal and its influence on therapeutic antimicrobial use.

Conclusion

Infectious disease management and grazing decisions are important elements of agropastoral livestock husbandry. Our results show strong relationships between communal grazing, livestock illness, and antimicrobial use. We estimate the impact of grazing patterns and prior livestock illnesses on antimicrobial demand using a zero-inflated Poisson regression model. Identification within this framework is achieved by making use of the variation in ethnicity of households in our sample. We also examine the relationship between current illness rates, grazing and antimicrobial use. Our results show that disease risk perceptions and communal grazing play important roles in determining disease outcomes and the demand for antimicrobials.

The paper relies on communal grazing and prior illness as indicators of underlying risk over which herd owners make antimicrobial use decisions. Communal grazing is directly linked with exposure and disease transmission, while prior illness is informative about current risk and can also have a psychological framing effect on pastoralist's beliefs about disease outcomes. Both communal grazing and prior illness are positively related to an increased probability of having antimicrobials on hand for livestock use. Prior livestock illness in the last month also is positively related to having more antimicrobials on hand. In turn, we find that communal grazing is positively related to the current number of sick animals, as is antimicrobial use. While we control for endogeneity using an instrumental variable approach, the positive relationship between antimicrobial use and current illness could reflect therapeutic antimicrobial use rather than a practice of using antimicrobials for prophylaxis (disease prevention).

There are externalities associated with both communal grazing and antimicrobial use. Although communal land tenure has important strengths as a property rights regime, especially in terms of risk management in volatile climate zones (Agrawal, 2001; Ostrom, 2015), it can incentivize overgrazing (Runge, 1981; Ciriacy-Wantrup and Bishop, 1975), and potentially be associated with disease transmission externalities to the extent that herds pass on disease to other herds sharing the communal grazing land. Antimicrobial use has two potentially offsetting effects that can be magnified by communal grazing. First, antimicrobial use that reduces the intensity and duration of pathogen shedding can reduce pathogen transmission to other herds, but it might also lead to a larger fraction of pathogen populations being antimicrobial resistant, leading to reduced effectiveness of future antimicrobial use. We show that through its potential to increase disease transmission rates, communal grazing may also exacerbate overuse of antimicrobials from an economic efficiency perspective. Therefore, for optimal communal grazing and antimicrobial use in terms of economic efficiency, it is important to align the private benefits of communal grazing and antimicrobial use with the social benefits related to the two activities. Although our data do not allow examination of how antimicrobial use in this context influences development of antimicrobial resistance, understanding incentives for antimicrobial use in agropastoralist systems may help devise strategies to limit the emergence and persistence of antimicrobial resistance in these populations.

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Figures

Figure 1: Northern Tanzania from Mt Meru to the southern slopes of Kilimanjaro, West to Ngorogoro showing major highways and location of ethnic groups sampled. Source: Google maps, http://bit.ly/2eG8ojK.

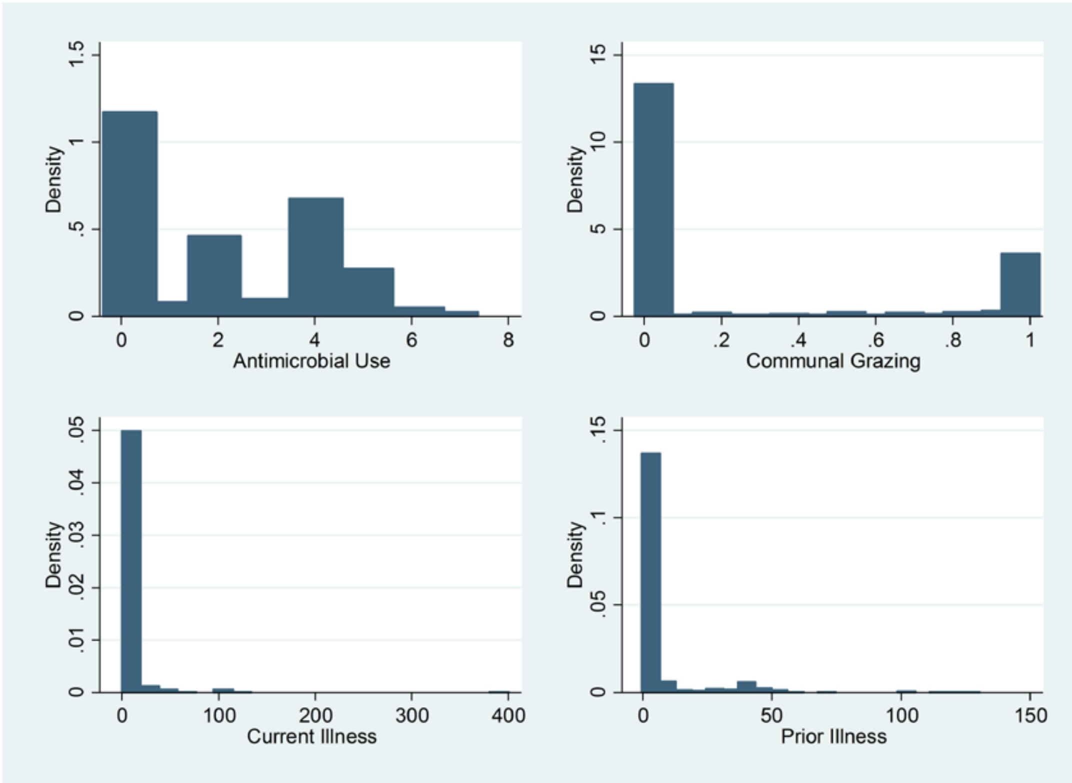

Figure 2: Histograms of *communal grazing* rates, *antibiotic use*, *prior illness* and *current illness* variables.

Tables

Table 1: Data descriptions

Variable	Description
Communal Grazing (g)	Fraction of owned animals that graze outside the homestead or compound.
Antimicrobial Use (a)	Number of types of antimicrobials in farm inventory. Guttman scale from 0-7. The inventories included four types of antibiotics (oxytetracycline, penicillin, streptomycin and sulfonamide and Tylosin), acaricides, anti-protozoal drugs and syringes and needles that indicated self-use.
Prior Illness (ρ)	The number of animals reported sick in the year, prior to current illnesses.
Current Illness (proxy for $\nu\gamma\alpha$)	The number of animals reported sick currently.
Sheep/Goats	Number of sheep and goats owned by a farm.
Cattle	Number of cattle owned by a farm.

Use Govt. Vet	Indicator variable equal to 1 if the farm uses the government veterinary services, zero otherwise.
Income	Total household income in Tanzanian currency.
Distance to Urban	This variable maps the log of distance from a household to an urban center in kilometers.
Distance to Market	This variable maps the log of distance from a household to a market in kilometers.
Household Size	Total number of people living in a household.
Rainfall	Indicator variable if village average annual rainfall is greater than average rainfall of the total region of the sample. Estimate of average annual precipitation, in inches, was calculated from years 2008 - 2013 from the weather stations located in the area. The average was calculated at 39.2 inches. https://mesonet.agron.iastate.edu/request/download.phtml?network=TZ__ASOS
Arusha	Indicator variable equal to 1 if household ethnicity is Arusha, 0 otherwise.
Chagga	Indicator variable equal to 1 if household ethnicity is Chagga, 0 otherwise.
Other	Indicator variable equal to 1 if household ethnicity is neither Maasai, Chagga, or Arusha, 0 otherwise.

Table 2: Summary statistics (N = 382).

	Mean	Standard Deviation	Min	Max
Antimicrobial Use	1.69	1.62	0	7
Communal Grazing	0.318	0.454	0	1
Prior Illness	15.04	28.66	0	130
Current Illness	11.02	33.99	0	400
Sheep/ Goat	76.97	200.16	0	2,415
Cattle	62.12	233.17	0	3,150
Income	960,821	1,520,000	0	3,800,000
Household Size	9.91	7.5	1	41
Use Govt. Vet	0.32	0.466	0	1
Rainfall (inches)	39.2	25.1	18.3	82.5
Distance to Urban (km)	46.26	41.22	3.58	174.91
Distance to Market (km)	3.08	6.15	0.1	60
Arusha (percent)	21.98	-	0	1
Maasai (percent)	50.72	-	0	1
Chagga (percent)	24.4	-	0	1
Other	2.9	-	0	1

Table 3: *Communal grazing* regression. Fractional Probit results.

Dependent Variable - *Communal Grazing*	Coefficient	Marginal Effects
Rainfall	-1.64***	-0.266
	(0.204)	
Chagga	-1.96***	-0.296
	(0.49)	
Arusha	-4.18***	-0.333
	(0.35)	
Other	-0.57	-0.12
	(0.51)	
Cattle	0.0026	0.001
	(0.002)	
Sheep/Goat	0.002	0.001
	(0.005)	
Govt. Vet.	-0.065	-0.011
	(0.28)	
Household Size	0.007	0.002
	(0.011)	
Income	-0.097	-0.016
	(0.16)	
Distance to Urban	1.02***	0.166
	(0.17)	
Distance to Market	0.023	0.003
	(0.084)	
Psuedo R-Squared	0.52	

Number of Observations = 382.

*, **, *** indicate statistical significance at 10, 5 and 1% respectively

Table 4: *Antimicrobial use* regression. Zero-Inflated Poisson.

Dependent variable: *Antimicrobial Use*	*Decision not to Use Antimicrobials* [a]	*Number of Antimicrobials*	*Marginal Effects*
Communal Grazing [b]	-20.67*** (6.50)	0.0352 (0.17)	3.71
Prior Illness	-3.05** (1.51)	0.206** (0.082)	0.877
Cattle	-0.008 (0.069)	0.0003 (0.00014)	0.001
Sheep/Goats	-0.005 (0.006)	0.002 (0.001)	0.001
Govt. Vet	2.96*** (0.72)	0.065 (0.098)	-0.299
Income	-0.10*** (0.03)	-0.003 (0.01)	0.013
Household Size	-0.026 (0.062)	0.0009 (0.004)	0.006
Rainfall	-4.71*** (0.93)	-0.035 (0.033)	0.833
Distance to Urban	0.604 (0.49)	0.042 (0.056)	-0.001
Distance to Market	0.91* (0.53)	0.019 (0.039)	-0.093
Vuong Test: ZIP vs Poisson			9.97
Likelihood Ratio Test (p-value): Poisson vs NB			0.5
Likelihood Ratio Test (p-value): ZIP vs ZINB			0.23

[a]The model predicts the outcomes of zero observations and therefore reported signs for the estimates here are for the probability of not choosing antibiotics.
[b]The predicted values from the regression summarized in Table 4 are used as the instrument for communal grazing.
*, **, *** indicate statistical significance at 10, 5 and 1% respectively.
N = 382.

Table 5: *Current Illness*, Zero-Inflated Poisson Regression.

	Regression 1		Regression 2	
Dependent Variable *Current Illness*	No Sick Animals	Number of Sick Animals	No Sick Animals	Number of Sick Animals
Communal grazing	0.23	1.14***	0.36	1.02***
	(0.34)	(0.097)	(0.41)	(0.102)
Antimicrobial use[a]	-	-	-0.81***	0.17***
			(0.14)	(0.034)
Sheep/Goats	-0.002	0.001**	-0.0013	0.009
	(0.008)	(0.0008)	(0.001)	(0.009)
Cattle	-0.0009	-0.003	-0.0008	-0.0075
	(0.0008)	(0.005)	(0.0008)	(0.005)
Rainfall	0.287	-0.059	-0.34	0.127
	(0.28)	(0.058)	(0.28)	(0.079)
Distance to Urban	-0.39**	0.061	0.175	-0.087
	(0.16)	(0.05)	(0.16)	(0.058)
Distance to Market	0.04	0.19***	0.06	0.20***
	(0.13)	(0.02)	(0.138)	(0.021)
Vuong Test Statistic	5.15		6.35	

*, **, *** indicate statistical significance at 10, 5 and 1% respectively.

[a]The predicted values from the regression summarized in Table 5 is used as the instrument for antimicrobial use. N=382.