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Can Free-Riding Be Beneficial? Optimal Antimicrobial Use Under Free-Riding And Resistance Externalities

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Abstract:

Over- or under-provision of antimicrobials in the livestock sector can be economically important in terms of livestock health, disease introduction and spread, and future costs of disease therapy. This paper examines optimal antimicrobial use under free-riding and resistance externalities in the context of small-holder farm households in developing countries, which are an important demographic in global food production. We first develop a model with free-riding incentives that elucidates the effects of free riding on antimicrobial use given disease dynamics. We then add antimicrobial resistance as a dynamic constraint and compare the two models, examining several cases conditional on the extent of the aforementioned externalities. Our model suggests a strong potential for over-provision of antimicrobials when ignoring resistance dynamics. Policy implications are discussed in light of the animal health and disease control subsidy programs of the developing world as well as unregulated antimicrobial sales and use.

JEL Classification: Q180; O130; I150
Keywords: Antimicrobials; antibiotic resistance; free ridership; livestock farming; animal health

1. Introduction

Small-scale agropastoralists in the developing world use antimicrobials for disease prevention and treatment and growth augmentation. However, the use of antimicrobials, especially for prophylaxis, can be suboptimal due to free-riding incentives (Gramig, Horan, and Wolf, 2009; Hennessy and Wolf, 2015; Bauch and Earn, 2004). Limited access to veterinary services, low availability of antimicrobials, and credit constraints can also hamper the demand for antimicrobials in small-holder agricultural households (Caudell et al., 2017). To overcome these access issues and free-rider problems associated with preventive antimicrobial use, some governments have designed subsidy programs to promote antimicrobial use in the livestock sector (Mwaseba and Kigoda, 2017).

Access, availability, and free ridership are not the only problems associated with antimicrobial use, hence subsidy programs that promote antimicrobial use in agriculture may end up having unintended consequences. The costs of morbidity and mortality have been increasing worldwide, largely owing to antimicrobial resistance (Laxminarayan et al., 2016), and the use of veterinary antimicrobials in livestock can be crucial contributors to emergence and transmission of antimicrobial resistance (Ahmed et al., 2017; Carlet et al., 2012; Van Boeckel et al., 2015). Since private decision makers may not account for the external costs imposed on other herd owners through resistance, they may overuse antimicrobials from a social economic perspective, exacerbating the emergence of antimicrobial resistance (Althouse et al., 2010; Secchi and Babcock, 2002; Laximinarayan and Brown, 2001; Brown and Layton, 1996).

We focus on the agricultural households and small-holder setting of the developing world. Small-holder farms of the developing world produce 80% of global food, making them an important yet under-studied demographic in antimicrobial demand and its impact on emergence

of antimicrobial resistance (Graeub et al., 2016; Omulo et al., 2015; Sarmah et al., 2006). Since commercial farms have easy access to antimicrobials (commonly used for prophylaxis and growth promotion) and less incentive to free ride given their share of the market and higher disease-risk burden, externalities associated with drug resistance may be more pronounced in that setting (Orzech and Nikter 2008; Levy 1998). In our setting, because of credit constraints and lack of availability, households are more likely to rely on their neighbors and local immunity to diseases rather than using antimicrobials for prophylaxis. Therefore, policy instruments like subsidies are used to promote antimicrobial use in farms of developing countries.[1]

The objective of this paper is to examine the optimal level of preventive antimicrobial use in agriculture under free-riding incentives in a small-holder, developing country setting accounting for antimicrobial effectiveness, modeled as non-renewable resource in a dynamic optimization framework, following the existing literature on economics of antibiotic resistance (Laxminarayan and Brown, 2001; Wilen and Msangi, 2003). Our initial model of free-riding incentives is fairly standard, and it elucidates the effects of free riding on antimicrobial use given disease dynamics. We then add antimicrobial resistance as a dynamic constraint and compare the two models, examining several cases conditional on the extent of both externalities. Policy implications are discussed in light of the animal health and disease control subsidy programs of the developing world as well as unregulated antimicrobial sales and use, which can be conceptualized as an implicit subsidy of sorts.

Free-riding and resistance externalities are modeled separately in the literature on antimicrobial use. Modeling the two separately could lead to two types of errors in policy prescription. Only modeling access issues and the free-rider problem could prescribe

[1] Two such policies have been discussed in the Discussion section of the paper.

subsidization policies, which in turn lead to increased antimicrobial use and resistance. Conversely, modeling only resistance could lead to policy that may limit or ban the use of antimicrobials where they are necessary for disease prevention or treatment. This paper contributes to the literature of antimicrobial use in the small-holder, developing country setting by modeling the two aforementioned externalities simultaneously in a dynamic model to account for the required balance between these countervailing moral hazard issues.

The next section develops the theoretical framework, first without the resistance dynamics and then with resistance dynamics and illustrates the resulting propositions. Section 3 illustrates and examines the simulation results and transition dynamics followed by a discussion and conclusions in Sections 4 and 5, respectively.

2. Theory

We consider the privately and socially optimal use of prophylactic antibiotics (or antimicrobials) for livestock in developing countries. First, we examine the difference between the competitive and social equilibrium for prophylactic antimicrobial use when antimicrobial resistance is not included in the model. We then incorporate antimicrobial resistance by adding a variable and dynamic constraint to our model. We find that individual households will under-provide antimicrobials relative to the socially optimal level when we ignore antimicrobial resistance. When we include antimicrobial resistance, the socially optimal amount of antimicrobial use could be higher or lower than private antimicrobial use and will depend on the relative sizes of free-riding and resistance externalities.

2.1 Model without antimicrobial resistance

Households maximize the expected value of their welfare over an infinite time horizon. For agropastoralists, welfare is determined largely by the health of their livestock. Suppressing

other sources of uncertainty (e.g., prices, capacity constraints, etc.) and assuming homogeneity in terms of herd size/livestock holdings, the expected value of a household's welfare (W) takes the following form:

$$W = \int_{t=0}^{\infty} \left[v\big(a(t) + \tilde{a}(t), p(t)\big) - ca(t) \right] e^{-rt} dt,$$

where $v(\cdot)$ is the value derived from keeping livestock, $a(t)$ is the household's antimicrobial use at time t, $\tilde{a}(t)$ is all other households' antimicrobial use, $p(t)$ is disease prevalence, r is the discount rate, and c is the cost of antimicrobials, which we treat as a constant. We assume the following intuitive relationships between the value of keeping livestock and its arguments:

$$v_a > 0,\ v_p < 0,\ v_{aa} < 0, \text{ and } v_{ap} = v_{pa} > 0.$$

In other words, the value of keeping livestock for small-holder farms in developing countries increases with antimicrobial use, but the magnitude of those marginal gains decreases as antimicrobial use increases. The value of keeping livestock decreases as the level of disease prevalence increases. The marginal value of antimicrobial use is increasing as disease prevalence increases, in the absence of resistance dynamics. Disease prevalence changes according to the following disease dynamics constraint:

$$\dot{p} = \theta\big(A(t)\big)\delta\big(p(t)\big),$$

where $A(t) = a(t) + \tilde{a}(t)$ is simply the current aggregate level of antimicrobial use, which individual decision makers treat as exogenous.[2] This aggregate term for antimicrobial use is

[2] While changes in $a(t)$ will have effects on $A(t)$, we assume that the individual household's contribution to $A(t)$ is sufficiently small – or conversely that $A(t)$ is sufficiently large in relation to $a(t)$ – that it can be ignored in the household's problem.

necessary to draw a distinction between the private and social optima, since private decision makers and the social planner optimize the same welfare functions with different arguments. We introduce $\theta(\cdot)$ to represent the way antimicrobial use reduces the change in disease-related pathogens without accounting for antimicrobial resistance. We assume that $\theta_A < 0$ and $\theta_{AA} > 0$, which represents the notion that antimicrobial use reduces disease prevalence at an increasing rate. The natural growth of disease prevalence is captured in $\delta(\cdot)$, and this function should follow some sort of an exponential path such that $\delta_p > 0$ and $\delta_{pp} > 0$. A multiplicatively separable form of the disease dynamics constraint is highly tractable and emphasizes the different effects antimicrobial use and current levels of prevalence can have on changes in the latter. This approach allows for interaction. Lastly, we assume the initial level of disease prevalence, p_0, is finite and known.

The private decision maker will solve the present-value maximization problem above for his private level of antimicrobial use: $\hat{a}(t)$. The social planner will maximize a similar equation to get optimal aggregate antimicrobial use, but she will internalize the reduction in disease prevalence stemming from aggregate antimicrobial use. We find that optimal private antimicrobial use is below the socially optimal level for each household (formal derivations are given in Appendix A). This result stems from an incentive structure under which households are not fully able to internalize the broader welfare effects of antimicrobials. As expected, free ridership tends to underprovide antimicrobials relative to the social optimum when ignoring resistance dynamics.

2.2 Model with antimicrobial resistance

To incorporate antimicrobial resistance, we modify our objective function to include an additional resistance variable that directly affects the value of livestock:

$$W = \int_{t=0}^{\infty} [v(a(t) + \tilde{a}(t), p(t), I(t)) - ca(t)]\, e^{-rt} dt,$$

where $I(t)$ is antimicrobial ineffectiveness such that $v_I < 0$ and $v_{II} > 0$, and partial derivatives defined above, in Section 2.1, remain unchanged. Higher levels of antimicrobial resistance diminish small-holders' values of keeping livestock, and the value decreases at an increasing rate. We also assume that $v_{AI} = v_{IA} < 0$, which indicates that as resistance increases, the marginal value of antimicrobials decreases.

Accounting for antimicrobial resistance in terms of its effects on disease prevalence, our disease dynamics constraint becomes:

$$\dot{p} = \theta\big(A(t), I(t)\big)\delta\big(p(t)\big).$$

Antimicrobial resistance affects the growth rate of disease prevalence both directly and indirectly through its interaction with aggregate antimicrobial use. Our modification of the disease dynamics constraint illustrates the more ambiguous effect of the $\theta(\cdot)$ function on changes in disease prevalence. An increase in antimicrobial use decreases the growth rate of disease prevalence, and antimicrobial resistance has an opposite effect ($\theta_A < 0, \theta_I > 0$). Further, we assume $\theta_{AA} > 0$ and $\theta_{II} > 0$, i.e., an increase in antimicrobial use hampers the growth of disease at an increasing rate and an increase in antimicrobial ineffectiveness increases the growth of disease prevalence at an increasing rate. To account for an interaction between antimicrobial use and antimicrobial resistance, we make the additional assumption that $\theta_{AI} = \theta_{IA} < 0$, i.e., the

marginal ability of antimicrobials to hamper the growth of disease prevalence goes down as antimicrobial resistance goes up.

The evolution of antimicrobial resistance is characterized by our resistance dynamics constraint,

$$\dot{I} = \xi\big(A(t)\big),$$

where $\xi(\cdot)$ is the rate at which antimicrobials become ineffective, and we assume this is increasing in antimicrobial use such that $\xi_A > 0$ and $\xi_{AA} > 0$. The effectiveness of antimicrobials is nonrenewable, so the level of ineffectiveness is finite, $I = [0, \bar{I}]$. The initial levels of disease prevalence and antimicrobial ineffectiveness, p_0 and I_0, are finite and known.

Based on our solutions in Appendices A and B, we can define the optimal levels of antimicrobial use derived in each model as follows:

- $A(t)$ represents the (aggregated) privately optimal level of antimicrobial use in the absence of antimicrobial resistance;
- $\hat{A}(t)$ represents the socially optimal level of antimicrobial use in the absence of antimicrobial resistance;
- $A^*(t)$ represents the (aggregated) privately optimal level of antimicrobial use when we include antimicrobial resistance dynamics; and
- $\hat{A}^*(t)$ represents the socially optimal level of antimicrobial use when we include antimicrobial resistance dynamics.

Since households do not internalize externalities in either case, we treat $A(t) \equiv A^*(t)$ as identical terms.

From these optimal levels derived in our models, we make three conjectures about the private and socially optimal levels of antimicrobial use under free ridership and antimicrobial resistance.

Proposition 1: $A(t) < \hat{A}(t)$.

Private decision makers under-provide antimicrobials to their livestock compared with the social optimum in the absence of antimicrobial resistance. This is a basic result of free ridership.

Proposition 2: $\hat{A}^*(t) \leq \hat{A}(t)$.

The socially optimal level of antimicrobial use when we exclude antimicrobial resistance from the model is at least as high as (and likely higher than) the socially optimal amount of antimicrobial use when we include resistance dynamics.

Proposition 3: *Based on specific cases, we have either (i)* $A \leq \hat{A}^* \leq \hat{A}$ *or (ii)* $\hat{A}^* < A < \hat{A}$.

Proposition 3 follows directly from Propositions 1 and 2.

Case (i): This is the case when the relative size of the free-riding externality is greater than the resistance externality; therefore, aggregate private antimicrobial use is less than or equal to the socially optimal level with either externality.

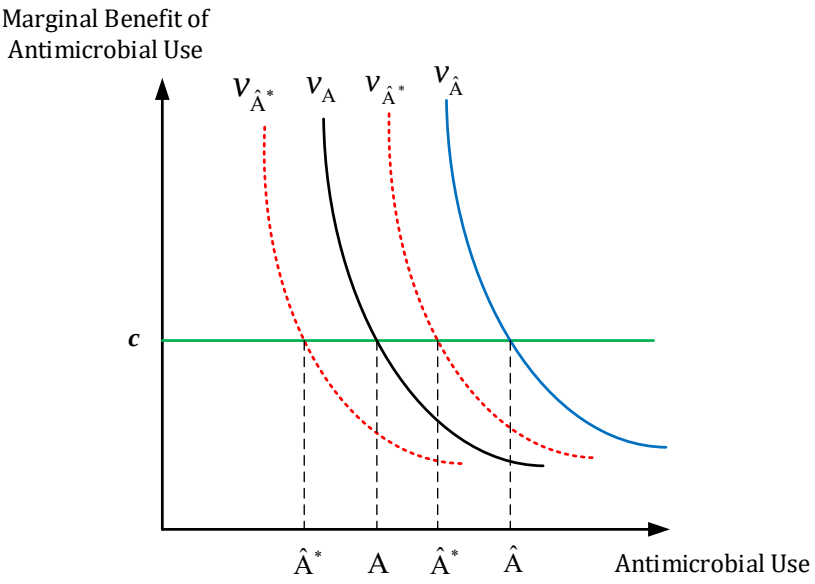
Case (ii): This is the case when the relative size of the free-riding externality is smaller than the resistance externality; therefore, socially optimal antimicrobial use with both externalities is less than aggregate private use, which is less than the socially optimal level with only the free-riding externality.

Together, Proposition 3 indicates that when we incorporate antimicrobial resistance dynamics into our model, the socially optimal amount of antimicrobial use is (1) never greater

than that in the no-resistance model, (2) may be lower than the privately optimal amount in the no-resistance model, and (3) may still be under-provided at the private level in the resistance model.

The three propositions above are presented graphically in Figure 1.

Figure 1. Marginal benefit of antimicrobial use as a public good accounting for antimicrobial resistance.



The marginal private and social benefits of antimicrobial use without accounting for antimicrobial resistance dynamics are given by v_A and $v_{\hat{A}}$, respectively. The marginal social benefit accounting for resistance dynamics, $v_{\hat{A}^*}$, is uncertain. It will be less than the marginal social benefit without resistance dynamics, but it is unclear where it will fall in relation to aggregate marginal private benefits without resistance dynamics.

3. Simulation

Given our model assumptions for the social planner problems, we construct phase diagrams in (A, p)-space examining the steady-state levels of antimicrobial use and disease prevalence in

both the no-resistance and the resistance cases. First, we must adopt some explicit functional forms and add parameters that satisfy the assumptions of our model. This exercise allows us to observe and make comparisons between the steady-state levels of antibiotic use and disease prevalence under the two alternative model specifications.

3.1 Parameterized illustration

The slope and curvature of $\dot{\rho} = 0$ and $\dot{A} = 0$ determine steady-state equilibrium and transition dynamics of disease prevalence and antimicrobial use (Figure 2). An upward sloping $\dot{\rho} = 0$ indicates that when disease prevalence is low (high) a small (large) amount of antimicrobials will keep the change in prevalence steady at zero. Conversely, $\dot{A} = 0$ slopes upwards indicating that to maintain no change in antimicrobial use over time, higher levels of antimicrobial use correspond to higher levels of disease prevalence.

Taking our present-value Hamiltonian for the dynamic problem without antimicrobial resistance, we can use the Maximum Principle to solve for the steady-state equilibrium. We begin by isolating our $\dot{A}$ equation:

$$\dot{A} = \frac{-\theta_A \delta v_p + 2(v_A - c)\theta\delta_p - v_{Ap}\theta}{v_{AA} - (v_A - c)\frac{\theta_{AA}}{\theta_A}}.$$

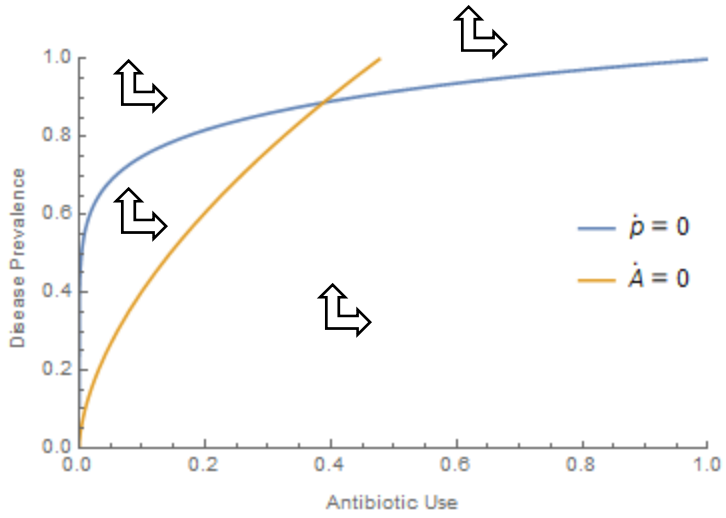
We select functional forms that satisfy our assumptions to demonstrate the transition dynamics as given in Table 1.

Table 1. Functional form selections for parameterized illustrations.

Function	No resistance dynamics	Resistance dynamics
Value of keeping livestock	$v(A,p) = A^{\kappa_1}p^{\kappa_2} - p^{\kappa_3}$	$v(A,p,I) = A^{\kappa_1}p^{\kappa_2}I^{\kappa_4} - p^{\kappa_3}$
Antimicrobial effects on disease prevalence	$\theta(A) = A^{\kappa_5}$	$\theta(A) = A^{\kappa_5}I^{\kappa_6}$
Independent rate of change in disease prevalence	$\delta(p) = p^{\kappa_7}$	$\delta(p) = p^{\kappa_7}$
Antimicrobial effects on antimicrobial resistance		$\xi(A) = A^{\kappa_8}$

Using parameter values of $\kappa_1 = 0.5$, $\kappa_2 = 1$, $\kappa_3 = 2$, $\kappa_5 = -0.25$, and $\kappa_7 = 2$, we can solve the initial model (without resistance dynamics) numerically for given levels of A and p. We plot the isoclines for $\dot{A} = 0$ and $\dot{p} = 0$ in Figure 2. As long as the parameter values satisfy the assumptions of the model, the qualitative results should be quite similar regardless of the parameters' magnitudes.

Figure 2. Phase diagram for initial model with freeriding but no explicit antimicrobial resistance



If antimicrobial use and prevalence are both initially below their steady-state levels, it is possible to converge on the steady-state equilibrium. However, if either exceeds its steady-state level, the system will diverge from the steady state and both antimicrobial use and prevalence will increase ad infinitum. The rationale behind this result is simple. If disease prevalence is too high at the beginning, then no amount of antimicrobial use will allow the level of prevalence to stop changing over time. Conversely, when antimicrobial use is too high, there is no way to reduce it without increasing the level of disease prevalence

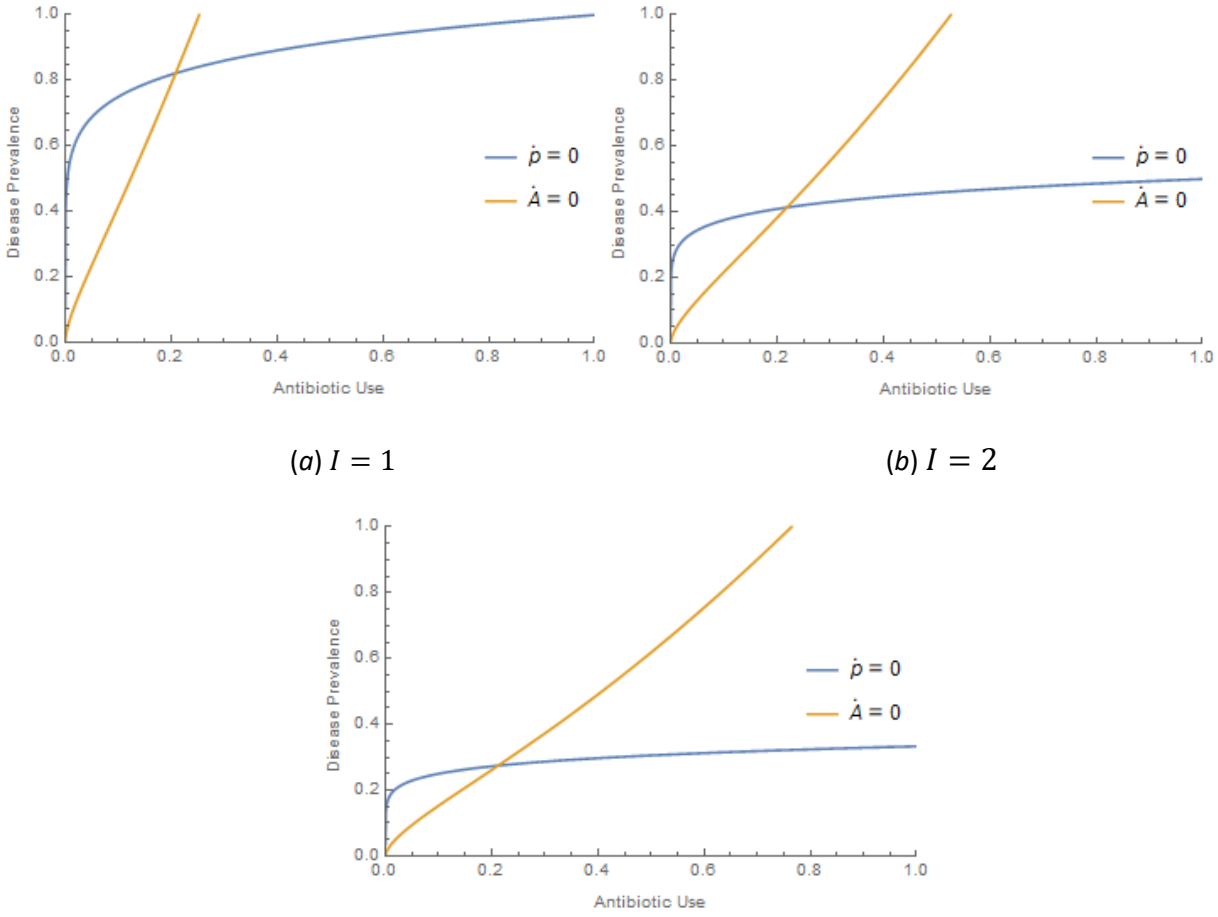
When we add our antimicrobial resistance variable to the model along with its dynamic constraint, we derive the associated $\dot{A}$ as

$$\dot{A} = \frac{-v_{Ap}\theta\delta - v_{AI}\xi + [v_p - \lambda\delta_p\theta]\theta_A\delta + \lambda\theta_{AI}\xi\delta + \lambda\theta_A\delta_p\theta\delta + [v_I - \lambda\theta_I\delta]\xi_A}{v_{AA} - \mu\xi_{AA} - \lambda\theta_{AA}\delta}.$$

In this case, we have three variables, so drawing a proper phase diagram requires a three-dimensional plot of isoplanes. Since we are only interested in differences from the initial steady state, we have opted to fix antimicrobial resistance at different levels to illustrate changes in the same (A, p)-space as we used in the initial diagram. When we fix antimicrobial resistance at different levels, we find that the steady-state levels of antimicrobials and disease prevalence begin to shift. Our parameters from above remain the same, but now we include $\kappa_4 = -0.5$, $\kappa_6 = 2$, and $\kappa_8 = 1.5$.

Figure 3 illustrates that as the level of antimicrobial ineffectiveness increases (at fixed levels, as shown across the three panels), the corresponding steady-state levels of antimicrobial use and disease prevalence decline. The higher the antimicrobial ineffectiveness, the lower the disease prevalence level that will be sustainable in steady state.

Figure 3. Phase diagrams for model with freeriding and resistance externalities



$(a)\ I = 1$ $(b)\ I = 2$

$(c)\ I = 3$

With higher levels of resistance, $\dot{A} = 0$ becomes more horizontal and lower. This indicates that the rate of change in antimicrobial use in equilibrium must be much higher to maintain a low level of disease prevalence in the presence of higher antimicrobial resistance. More importantly, the equilibrium level of antimicrobial use that is sustainable under our antimicrobial resistance framework is lower than the level sustainable in the free-rider model. This parameterized illustration further demonstrates our theoretical result in Proposition 2.

4. Discussion

In our model, the optimal use of antimicrobials is determined by the relative size of the free-riding and resistance externalities. We discuss the implications of these results in light of subsidy programs like the Tanzanian Acaricide Subsidy Program[3] and Turkey's Animal Health Subsidy Program[4]. These programs are structured to incentivize farmers to protect their animals from disease risk and overcome free-riding behaviors, and in so doing these subsidies may incentivize the prophylactic overuse of antimicrobials. Our model emphasizes the need to recalibrate these policies by incorporating antimicrobial resistance externalities in decision calculus. If these programs lead to injudicious use of antimicrobials, then the policies could be detrimental to public health through their contribution to resistance development.[5]

If the case $A > \hat{A}^*$ arises, given our disease dynamics, then free riding may not be such a detrimental behavior, and it may in fact lead the economy closer to the socially optimal level of antimicrobial use. We cite the two subsidy programs above specifically to motivate the presence of such direct interventions; however, there are other policies that maybe regarded as indirect subsidies and can incentivize overuse much like direct subsidies. For example, the over-the-counter availability of antimicrobials without prescription, which can be regarded as a subsidy on transaction costs, can be a major issue in developing countries (Orzech and Nikter, 2008; Carlet et al., 2012). Furthermore, self-prescription leads to consumption of more broad-spectrum antibiotics (Ahmed et al., 2017; Caudell et al., 2017) and may pose the threat of more strains of bacteria becoming resistant more rapidly.

[3]http://www.snv.org/public/cms/sites/default/files/explore/download/brief_1_public_accountability_in_tanzania_pata_initiative.pdf

[4]https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Turkish%20Livestock%20Support%20and%20Subsidies_Ankara_Turkey_8-12-2015.pdf

[5] Our model also can motivate the problem of pest resistance in target species. However, policies to mitigate resistance in bacteria and pests may be different.

In the case where the relative size of the free-riding externality is greater than the resistance externality (i.e., when $\hat{A}^* < A$), incentives may be required to deal with under-provision of livestock health inputs. However, if policymakers do not account for the antimicrobial resistance externality, they may end up over-incentivizing the use of antimicrobials. Further data collection is required that can measure these externalities and prescribe incentives to increase or decrease antimicrobial use according to the relative sizes of these externalities.

5. Conclusion

The countervailing effects of free-riding and resistance externalities in antimicrobial use in a small-holder, developing country setting may result in sub-optimal levels of disease control, which in turn may lead to high disease prevalence due either to a lack of livestock health inputs or to reductions in the inputs' effectiveness. This paper examines the optimal level of preventive antimicrobial use under free-riding incentives in a small-holder, developing country setting given antimicrobial effectiveness, which we have modeled as non-renewable resource in a dynamic optimization framework. Our first model is a standard model with free-riding incentives that elucidates the effects of free-riding on antimicrobial use given disease dynamics. We then add antimicrobial resistance as a dynamic constraint and compare the two models, examining several cases conditional on the extent of both externalities. Policy implications are discussed in light of the animal health and disease control subsidy programs.

This paper contributes to the literature of antimicrobial use in the small-holder, developing country setting by modeling the free-riding and resistance externalities simultaneously. If policymakers fail to account for both of these externalities and instead account

only for free ridership, the resulting policies could aim to overprovide antimicrobials relative to the true socially optimal levels including resistance dynamics. This oversight could increase disease transmission and prevalence, and it may lead to disease introduction and spread in the herd as well as the community. On the other hand, if pathogens become resistant to antimicrobials, future costs of disease will rise in terms of increased mortality and increased duration of illness. Therefore, the paper emphasizes the need to align the private benefits of antimicrobial use with the social benefits of these inputs, accounting fully for free riders and increasing levels of disease resistance associated with antimicrobial use.

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Appendix A: No antimicrobial resistance

The private decision maker's problem is:

$$W = \int_{t=0}^{\infty} \left[v\big(a(t) + \tilde{a}(t), p(t)\big) - ca(t)\right] e^{-rt}\, dt$$

$$s.t. \qquad \dot{p} = \theta\big(A(t)\big)\delta\big(p(t)\big)$$

$$p(0) = p_0$$

Private households maximize present value Hamiltonian:

$$H = v(a + \tilde{a}, p) - ca - \lambda\theta(A)\delta(p)$$

The maximum principle gives us the following:

$$H_a = v_a - c = 0 \qquad \text{(First-Order Condition)}$$

$$\dot{\lambda} = v_p - \lambda\theta\delta_p \qquad \text{(Portfolio Balance Condition)}$$

$$\dot{p} = \theta\delta \qquad \text{(Dynamic Constraint)}$$

Summing over all individuals, we get $Nv_A - Nc = 0$, which is the same as $v_A - c = 0$. The social planner's problem in which the benevolent planner internalizes the reduction in disease persistence that comes from aggregate antimicrobial use gives use the following:

$$H_A = v_A - c - \lambda\theta_A\delta = 0 \qquad \text{(First-Order Condition)}$$

$$\dot{\lambda} = v_p - \lambda\theta\delta_p \qquad \text{(Portfolio Balance Condition)}$$

$$\dot{p} = \theta\delta \qquad \text{(Dynamic Constraint)}$$

With the aggregate private antimicrobial use denoted as A and the socially optimal as $\hat{A}$, we can compare the private and social first-order conditions:

$$v_A - c = v_{\hat{A}} - c - \lambda\theta_{\hat{A}}\delta$$

$$v_A = v_{\hat{A}} - \lambda\theta_{\hat{A}}\delta$$

which implies that $v_A > v_{\hat{A}}$, since $\theta_{\hat{A}} < 0$. Based on the shape of the value function $v(\cdot)$, this implies $\hat{A} > A$. In other words, private antimicrobial use will be lower than the socially optimal level, so the market is inefficient in providing antimicrobials.

Appendix B: Antimicrobial resistance

We modify the problem now to include disease prevalence and a disease resistance dynamic constraint:

$$W = \int_{t=0}^{\infty} [v(a(t) + \tilde{a}(t), p(t), I(t)) - ca(t)]\, dt$$

$$s.t. \qquad \dot{p} = \theta\big(A(t), I(t)\big)\delta\big(p(t)\big)$$

$$\dot{I} = \xi(A(t))$$

$$I(0) = I_0,\ p(0) = p_0 \text{ and } I \in [0, \bar{I}]$$

Private household with antimicrobial resistance

$$H = v(a + \tilde{a}, p, I) - ca - \lambda[\theta(A, I)\delta(p)] - \mu[\xi(A)]$$

The maximum principle gives us the following:

$$H_a = v_a - c = 0 \qquad \text{(First-Order Condition)}$$

$$\dot{\lambda} = v_p - \lambda\theta(A, I)\delta_p \qquad \text{(Portfolio Balance Condition 1)}$$

$$\dot{\mu} = v_I - \lambda\theta_I\delta \qquad \text{(Portfolio Balance Condition 2)}$$

$$\dot{p} = \theta(A, I)\delta \qquad \text{(Dynamic Constraint 1)}$$

$$\dot{I} = \xi(A) \qquad \text{(Dynamic Constraint 2)}$$

Summing over all individuals, we get $Nv_A - Nc = 0$, which is the same as $v_A - c = 0$.

The social planner internalizes the effects of aggregate use on disease prevalence and antimicrobial ineffectiveness. Solving the social planner's problem gives the following:

$$H_A = v_A - c - \lambda\theta_A p - \mu\xi_A = 0 \qquad \text{(First-Order Condition)}$$

$$\dot{\lambda} = v_p - \lambda\theta(A, I)\delta_p \qquad \text{(Portfolio Balance Condition 1)}$$

$$\dot{\mu} = v_I - \lambda\theta_I p \qquad \text{(Portfolio Balance Condition 2)}$$

$$\dot{p} = \theta(A, I)\delta \qquad \text{(Dynamic Constraint 1)}$$

$$\dot{I} = \xi(A) \qquad \text{(Dynamic Constraint 2)}$$

We cannot directly compare the two socially optimal choices of antimicrobials since there are multiple unknowns in each, but we can compare them indirectly using the private problem. Considering antimicrobial use in the resistance case as $\hat{A}^*$ and the private case as A^*, we have

$$v_{A^*} - c = v_{\hat{A}^*} - c - \lambda\theta_{\hat{A}^*}\delta - \mu\xi_{\hat{A}^*}$$

$$v_{A^*} = v_{\hat{A}^*} - \lambda\theta_{\hat{A}^*}\delta - \mu\xi_{\hat{A}^*}$$

Recalling that $\theta_{\hat{A}^*} < 0$ and $\xi_{\hat{A}^*} > 0$, we have the following cases:

(1) $v_{A^*} \geq v_{\hat{A}^*}$ if $|\lambda\theta_{\hat{A}^*}\delta| \geq |\mu\xi_{\hat{A}^*}|$, which implies that $A^* \leq \hat{A}^*$; and

(2) $v_{A^*} < v_{\hat{A}^*}$ if $|\lambda\theta_{\hat{A}^*}\delta| < |\mu\xi_{\hat{A}^*}|$, which implies that $A^* > \hat{A}^*$.

This allows us to construct our conditional propositions above, in Section 2.