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# ANIMAL HEALTH AND THE ROLE OF COMMUNITIES: AN EXAMPLE OF TRYPANASOMOSIS CONTROL OPTIONS IN UGANDA

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# ABSTRACT

In many African countries, governments are re-thinking the role of the state in centrally providing certain goods and services. The rights and responsibilities for providing various public goods are being decentralized to lower levels of government administration, and/or being devolved directly to local citizens or user groups themselves. It is thus critical to ask: under what circumstances will local groups provide the socially optimal level of the public good? In this paper, we apply this question to the case of controlling an important vector-borne livestock disease in Uganda, trypanosomosis, which is transmitted by the tsetse fly. We investigate the underlying epidemiology of transmission and different options for control, and the implications for group provision of control, within the framework of a game-theoretic model. Results indicate that individual incentives to uptake tsetse and trypanosomosis control differ widely across different control methods. Since the costs of successfully implementing collective action are affected by individual incentives to participate in collective action, the model predicts which method/s are likely to be successfully implemented at the community level. More broadly, the model highlights under what circumstances community-provision is not likely to be optimal, depending on the underlying epidemiology of the disease, technological parameters, prevailing market characteristics, and socio-cultural conditions.

**Keywords:** public goods, collective action, vector-borne disease, animal health

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## 1. INTRODUCTION

Tsetse-transmitted trypanosomosis in Africa is a serious constraint to both animal agriculture and human health. Trypanosomosis of cattle, due to tsetse-transmitted *Trypanosoma congolense*, *T. vivax* and *T. brucei* occurs widely in sub Saharan Africa (SSA). Estimates of the land area affected range from approximately 8 – 11 million square kilometers, inhabited by 260-300 million people and 45-50 million cattle. Estimates of total losses due to trypanosomosis range from USD 1.3 – 5 billion depending on the methodology used, assumptions made, and type of loss estimated. Swallow (1997) estimates that each year in SSA, milk and meat offtake are 10-40% lower due to trypanosomosis infections, and that cattle numbers would increase by 37% in sub humid and 70% in humid zones if trypanosomosis were to be eradicated. He also concludes that in countries with large areas affected by trypanosomosis, total agricultural production is reduced by 2-10% (the crude relationship is that a 50% increase in livestock numbers would increase total agricultural output by 10%). In humans, the United Nations (UN Wire, 2000) estimates there may be as many as 300,000 new cases (tenfold higher than reported cases) of human trypanosomosis (sleeping sickness) annually among the 45 million rural Africans at risk.

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There are a number of tsetse and trypanosomosis control options, including large-scale aerial and ground spraying of insecticides, sterile insect techniques, use of trypanotolerant livestock breeds, use of insecticides directly applied to livestock (in the form of pour-ons or sprays), use of odor-baited traps and/or pesticide treated targets, and the use of trypanocidal drugs (chemotherapy and chemo prophylaxis). Large-scale spraying campaigns have largely been terminated because of serious adverse environmental and potential human health effects; sterile insect techniques are fairly new and require implementation at a very large-scales and thus very large outlays. Trypanotolerant livestock may be promoted at the community level and adopted by individuals; but to date, there are very few trypanotolerant cattle in southeastern Uganda[4]. In this paper, we consider the latter three control strategies, which can be adopted at either the community or individual level: trypanocidal drugs, tsetse control/eradication using insecticidal pour-ons or sprays, and tsetse control/eradication using insecticidal targets and traps.

These control methods have various advantages and disadvantages. Trypanocidal drugs are the most widely used treatment and control measure applied by individual farmers. Total expenditure on trypanocides in sub-Saharan Africa has been estimated at between USD 12 and 35 million per year, or between 30 – 87 million doses (Sones, 1999; Kristjanson et al., 1999). The three common trypanocidal compounds (isometamidium, diminazene and homidium) have been used in cattle for more than 30 years and represent 40%, 33% and 26% of the market respectively. One disadvantage to drug use is

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[4] Generally speaking, trypanotolerant cattle species have been identified and studied in West and Central Africa (D'Ietern et al., 1998), though others argue that certain east African breeds are also trypanotolerant (Dolan, 1998). The breeds generally found in our study area are not, however, considered to be trypanotolerant.

resistance, a problem which has been reported from many countries. Recent surveys conducted by the International Livestock Research Institute and its partners have shown a high proportion of resistant trypanosomes under circumstances of high trypanosomosis risk and trypanocidal drug use (Ethiopia > 90%; Burkina Faso, Kenya, Tanzania > 50%). Another disadvantage to drugs is the relatively small impact drug use appears to have on reducing overall prevalence (McDermott & Coleman, 2001).

Insecticidal pour-ons and sprays applied to individual animals protect the individual animal from trypanosomosis and from other biting fly/tick diseases, and also have a relatively large impact on tsetse mortality and thus on overall prevalence of the disease. There are thus private and public benefits to the use of pour-ons. Disadvantages include the relatively high costs of pour-ons needed to treat animals, and potential free-riding behavior due to the positive externalities in use[5]. Finally, stationary odor-baited traps or pesticide-treated targets (hereafter referred to as traps/targets) can be placed throughout a geographic area (based on tsetse distribution and human/livestock movements) to increase tsetse mortality and reduce prevalence of trypanosomosis. Traps and targets appear to be the most efficacious in reducing prevalence, but benefits are a pure public good; there are no private benefits in the form of individual animals protected nor are there benefits from reducing other biting fly and/or tick diseases. To date, almost all community-based traps/targets projects have been supported by external agents (governments, donors, Non-Governmental Organizations) with varying degrees of community participation, while the distribution of pour-ons have been supported by projects or paid for by individual farmers.

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[5] There may also be negative environmental externalities of using pour-ons, when cattle leave pour-on residues on fauna immediately following treatment. We do not explore this potential externality further in this paper.

Given these multiple control options, it is important to compare relative returns to guide trypanosomosis control decision-making. This is particularly important at the present time since, under the current "development" paradigm of devolution and decentralization of responsibilities to the local level, national governments are retrenching from activities in tsetse control and/or donor-sponsored initiatives are focusing explicitly on community-based strategies for tsetse and tryps control (Brightwell et al., 2001). In this climate, it is worth taking a close look at the underlying incentive structure for individuals in a community to cooperate in, or deviate from, agreements to provide various control methods. To do so, we develop an economic model based on an underlying epidemiological model of trypanosomosis (McDermott & Coleman, 2001). Because in the current policy environment the emphasis is on community-based measures of tsetse and trypanosomosis control, we derive the social optimum level of traps/targets, pour-ons, and drug use and compare these with outcomes arising from a non-cooperative game. It is particularly important to highlight the difference between the social optimum and outcomes arising from a non-cooperative game, as this difference is likely to reflect the cost of making and enforcing agreements on tsetse and trypanosomosis control at the community level.

In section 2, we develop the basic maximization model for the social optimizer and the individual, and highlight the role of the underlying epidemiology of trypanosomosis (hereafter referred to as tryps). In section 3, we derive the levels of traps and targets obtained under the social optimum and the non-cooperative game; we do the same for pour-ons in section 4, and for drug use in section 5. In the basic model, we consider that the choice of herd size is not a function of others' animals; in section 6, we extend the model to allow for a non-cooperative game to be played over the use of common pastures as well as in the provision of tsetse and/or tryps control measure. Section 7 summarizes the results and discusses the implications for current policy measures, and section 8 concludes.

## 2. THE BASIC MODEL

### 2.1 BASIC ECONOMIC MODEL FOR THE INDIVIDUAL AND THE SOCIAL OPTIMIZER

We start by considering the individual's maximization problem. The basic maximization model is written as follows:

$$\max_{x_i,cm_i} \pi_i = \Big[T_i\left(cm_i\right)+k_{OD}\left(1-T_i\left(cm_i\right)\right)*\Big[P_H\left(CM\right)+k_{Tryp}\left(1-P_H\left(CM\right)\right)\Big]\Big]*R_i\left(x_i\right)-\bar{c}_{cm}cm_i-\bar{c}_x x_i \qquad [1]$$

$$s.t. P_H\left(CM\right)\leq 1; \quad T_i\left(cm_i\right)\leq 1;$$

The first term, $T_i$, gives the proportion of animals that have been directly treated in the herd of person *i*, with control method, $cm_i$. The proportion of untreated animals is given by $\left(1-T_i\right)$, and here we also assume that all untreated animals will suffer a proportionate reduction in output from "other diseases", the proportionate reduction being captured by $k_{OD}$. In other words, treatment in the above representation protects the animals from both other diseases and trypanosomosis (hereafter referred to as tryps) simultaneously. The fraction of untreated that remain healthy of tryps is given by $P_H$, and the fraction of untreated animals that become infected is given by $\left(1-P_H\right)$. Untreated animals that become infected with tryps suffer an additional proportionate reduction in output equal to $k_{Tryp}$. In the above formulation, both the fraction treated and the fraction of untreated animals that become infected with tryps may be functions of the total amount of the control method used in the community, $CM = \sum cm_i$. In other words, the control method may increase the proportion of healthy animals in the herd directly through treatment, and indirectly, by reducing infection prevalence and thus reducing the proportion of untreated animals that become infected[6].

$R_i(X)$ is gross revenue product (output price times total production), where $X$ is the total number of livestock held. In the above specification, healthy animals simply provide gross returns of $R_i(X)$, and sick animals provide a fraction of the gross returns of healthy animals (c.f. Romney et al. 1995, Swallow, 2001). Costs of the control method and of animals are assumed to be constant, and are denoted by $\overline{c}_{cm}$ and $\overline{c}_X$, respectively.

In contrast to the individual's maximization problem, below is the basic maximization problem for the social optimizer:

$$\max_{x_i, cm_i} \pi_i = \sum_i \left[ T_i(cm_i) + k_{OD}\left(1 - T_i(cm_i)\right) * \left[ P_H(CM) + k_{Tryp}\left(1 - P_H(CM)\right) \right] \right] * R_i(x_i) - \overline{c}_{cm} cm_i - \overline{c}_x x_i$$

$$s.t. P_H(CM) \leq 1; \quad T_i(cm_i) \leq 1;$$

## 2.2 BASIC EPIDEMIOLOGICAL MODEL

In order to solve for the optimal amount of control measure to provide for either the social optimizer or the individual, we need to have a model of the equilibrium infection prevalence and how control measures affect that prevalence. We borrow

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[6] Certain control methods, i.e. tsetse traps and targets, directly reduce tsetse numbers but there is no direct impact on the proportion of treated animals.

heavily from an equilibrium prevalence model proposed in McDermott and Coleman (2001), which itself is based on the Ross-Macdonald framework for malaria transmission modified by Rogers (1988) to incorporate basic features of tsetse-transmitted trypanosomosis. The equilibrium prevalence is derived from a dynamic transmission model; in this paper we will only be concerned with evaluating equilibrium prevalence and not the dynamic path of transmission. Below we present the equilibrium tsetse reproductive ratio, designated by $R_0$, which captures the number of secondary infections resulting from an additional infectious host entering a population of susceptibles:

$$R_0 = \frac{e^{-uT}}{u} * \frac{ca^2bm}{r}$$

where $u$ is the tsetse mortality rate, $T$ is the incubation period required for the parasite to mature in tsetse fly, $c$ is the probability of a susceptible animal becoming infected from biting an infectious fly, $a$ is the daily biting rate of flies, $b$ is the probability of a fly becoming infected from an infected cow, $m$ is the ratio of tsetse flies to host animals, and $1/r$ is the duration of infection in cattle. The equilibrium prevalence of the parasite in the host population is given by:

$$Host\,\mathrm{Pr}\,evalence = \frac{R_0 - 1}{R_0 + \frac{ac}{u}}$$

If we assume that all infected animals become sick, so that the proportion sick is equal to disease prevalence in the host, we can write the proportion of healthy animals as follows:

$$P_H = \frac{\frac{ac}{u} + 1}{R_0 + \frac{ac}{u}}$$

Next, letting $\varphi = ca^2b$ and *rinv*=1/*r*, substituting for $R_0$ in the above expression, and rearranging the terms gives the following:

$$P_H = \frac{ac+u}{e^{-uT}\varphi\, m\, rinv + ac}$$

In the next three sections, we consider the impact of alternative control measures on infection prevalence and on the number of treated animals. As discussed in the introduction, there are three types of control measures considered in turn in this paper: traps and targets, pour-ons, and trypanocidal drugs. Traps and targets have no impact on the number of treated animals, but do increase the proportion of healthy animals by reducing prevalence via an increase *u*, the tsetse mortality rate, and it may also reduce the fly:host ration, *m*[7]. The use of pour-ons, like traps and targets, increases the tsetse mortality rate and may reduce *m*. However, there is an additional direct impact from using pour-ons, which is the increase in the number of treated animals. Trypanocidal drug use directly increases the number of treated animals, but we assume that there are no direct impacts on equilibrium prevalence[8].

While all models are built on simplifying assumptions, we note here that a major simplifying assumption in this model is that the number of treated cattle does not have a direct impact on equilibrium prevalence. That is, whereas we allow fly density to change with a reduction in the number of flies, we assume that it does not change with decreases in the number of susceptible cattle. This assumption might be reasonable for cases where

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[7] In the next section, we will first consider the impact of traps and targets when there is no additional impact on fly densities, and consider this to represent the case where reinvasion from surrounding areas occurs each period (McDermott & Coleman, 2001). Allowing for an impact on fly:vector ratio captures the case where reinvasion does not occur, or does so incompletely.

[8] As noted above, empirically there seems to be little benefit from drug use in terms of reduced prevalence (McDermott & Coleman, 2001).

there are many host species, where the marginal impact on fly densities might reasonably be considered to be zero or close to zero. This is done so that we can highlight decisions on both the optimal choice of the control measure to apply and the optimal number of livestock to hold. Incorporating this additional possible impact would significantly complicate evaluating the non-cooperative game outcomes, and such an extension would require numerical simulation.

## 3. PROVISION OF TRAPS AND TARGETS

We first evaluate the impact of traps and targets on tsetse mortality rate, *u*; to do so, it is convenient to let $\phi = \varphi \ m \ rinv$ so that

$$P_H = \frac{ac+u}{\phi e^{-uT} + ac}$$

We note that:

$$\frac{\partial P_H}{\partial u} = \frac{\phi e^{-uT}\left(1+T\left(ac+u\right)\right)+ac}{\left(\phi e^{-uT}+ac\right)^2} > 0 \qquad [2]$$

$$\frac{\partial^2 P_H}{\partial u^2} = \frac{\phi e^{-uT} T\left(2*\left(\phi e^{-uT}+ac\right)+T\left(ac+u\right)\left(\phi e^{-uT}-ac\right)\right)}{\left(\phi e^{-uT}+ac\right)^3} \leq\geq 0 \qquad [3]$$

Equations 2 and 3 above imply that the proportion of healthy animals may very well increases at an increasing rate with respect to changes in tsetse mortality. Because of the implications of the sign of equation 3 for the shape of the overall profit function, we are interested in characterizing the conditions under which equation 3 is positive. A sufficient condition for reductions in mortality to be increasing at an increasing rate is that $\frac{ac}{u} < 1$. This ratio, $\frac{ac}{u}$, has been termed the "stability" index (MacDonald, 1957); basically, when the ratio is greater than 1, disease is characterized by "good transmission", so that prevalence is relatively stable and robust to "shocks". When the ratio is less than one, prevalence is characterized as unstable, and the disease is more likely to disappear if the system is subject to shocks. Thus in areas with fluctuating disease prevalence, returns to control methods might be increasing at an increasing rate, which is quite intuitive.

Consider next an additional impact of traps/targets via a reduction in the fly:host ratio. This additional impact is as follows:

$$\frac{\partial P_H}{\partial m} = -\frac{e^{-uT}\varphi\left(ac+u\right)}{\left(e^{-uT}\varphi mrinv + ac\right)^2} < 0 \qquad [4]$$

with second derivative:

$$\frac{\partial^2 P_H}{\partial (m)^2} = \frac{2\left(\left(e^{-uT}\varphi\right)^2\left(ac+u\right)\right)}{\left(e^{-uT}\varphi mrinv + ac\right)^3} > 0 \qquad [5]$$

Given that a control method will always reduce the fly:host ratio, the above equations imply that doing so will increase the proportion healthy at an increasing rate.

Thus, if the control method has a separate impact on *m*, it is more likely that the profit function is convex, *ceteris paribus*.

Given these basic epidemiological relations, we can now return to the maximization problem. Denoting the use of traps and targets by person *i* as $cm_{tt-i}$ , and the total number of traps and targets as $CM_{tt} = \sum_{i=1} cm_{tt-i}$ ,we re-write the basic maximization problems as follows:

$$\max_{x_i, cm_{tt-i}} \pi_i = \left[T_i + k_{OD}\left(1-T_i\right)*\left[P_H\left(CM_{tt}\right)+k_{tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right]\right]*R_i\left(x_i\right)-\bar{c}_{cm_{tt}}cm_{tt-i}-\bar{c}_x x_i$$

$$s.t. P_H\left(CM_{tt}\right) \leq 1$$

where $CM_{tt} = \sum_{i=1} cm_{tt-i}$

To simplify notation in this next section, we note that traps/targets do not affect the number of treated animals, and rewrite the maximization problem setting $T_i = 0$ :

$$\max_{x_i, cm_{tt-i}} \pi_i = k_{OD}\left[P_H\left(CM_{tt}\right)+k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right]*R_i\left(x_i\right)-\bar{c}_{cm_{tt}}cm_{tt-i}-\bar{c}_x x_i$$

We initially assume that gross livestock revenue is a function of only the individual's own herd. This assumption might reflect a situation where stocking rates are relatively light, or where animals are kept on private fields and/or grass is cut and carried. In section 6, we relax this assumption and allow for a non-cooperative game to be played over grazing pressure on a common pasture as well as in the provision of a trypanosomosis control.

Considering first the case where traps/targets have an impact only on tsetse mortality, the following first-order conditions arise from the individual's profit maximizing calculus:

$$\frac{\partial \pi_i}{\partial cm_{tt-i}} = k_{OD}\left[\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{tt-i}}\left(1-k_{Tryp}\right) * R_i\right] - \overline{c}_{cm} = 0 \qquad [6]$$

$$\frac{\partial \pi_i}{\partial x_i} = k_{OD}\left[P_H\left(CM_{tt}\right) + k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right] * \frac{\partial R_i}{\partial x_i} - \overline{c}_x = 0 \qquad [7]$$

$$\forall i$$

The social optimizer (SO), on the other hand, considers the effect of an increase in $cm_{tt-i}$ on all households in the affected area. Recalling that $P_H(CM_{tt}) = P_H\left(\sum_{i=1} cm_{tt-i}\right)$, the SO problem may be written as:

$$\max_{x_i, cm_{tt-i}} \sum \pi_i = \sum\left[k_{OD}\left[P_H\left(CM_{tt}\right) + k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right]\right] * R_i\left(x_i\right) - \sum \overline{c}_{cm} cm_{tt-i} - \sum \overline{c}_x x_i$$

$$s.t. P_H\left(cm_{tt}\right) \leq 1$$

which gives the following first-order conditions:

$$\frac{\partial \pi_i}{\partial cm_{tt-i}} = k_{OD}\left[\sum \frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{tt-i}} * \left(1-k_{Tryp}\right) * R_i\right] - \overline{c}_{cm} = 0 \qquad [8]$$

$$\frac{\partial \pi_i}{\partial x_i} = k_{OD}\left[P_H\left(CM_{tt}\right) + k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right] * \frac{\partial R_i}{\partial x_i} - \overline{c}_x = 0 \qquad [9]$$

For traps and targets, then, we have the standard pure public good result where the individual only considers the marginal benefits from the public good accruing to him/herself as captured in Eq [6], whereas the social optimizer considers the impact of an increase in the control measure by any individual household on all households, as captured in Eq [8]. As derived in appendix 1, the amount of the control method provided is always higher under the social optimum. And, because the difference between the non-cooperative outcome and the social optimum is the sum of marginal benefits accruing to other members, this difference increases with the number of members (also proved in appendix 1). Given that prevalence is lower and proportion healthy animals is higher under the social optimum, the optimal number of animals to stock is clearly higher under the social optimum, as can easily be seen by examining equations [7] & [9]. It is worth emphasizing that more animals are stocked under the social optimum than under non-cooperation because of the assumption that the production function is only a function of each individual's own herd size and other household-specific parameters. Thus there are no implications to be drawn here about "overgrazing", since there are no externalities in use of pastures at this stage.

The above results define a unique interior solution only when the second order conditions for a maximum hold, and so we next consider the conditions under which the second-order condition holds. We make the standard assumption that livestock production is concave $\left(\frac{\partial R_i}{\partial x_i}>0,\ \frac{\partial^2 R_i}{\partial x_i^{\,2}}<0\right)$, and that the control method to increase tsetse mortality also exhibits diminishing marginal returns, $\frac{\partial u}{\partial cm_{tt-i}}$>0 and $\frac{\partial^2 u}{\partial {cm_{tt-i}}^2}$<0. However these assumptions are not enough to ensure that the profit function is quasi-concave, since this also depends on $\frac{\partial^2 P_H}{\partial u^2}$, which can be greater than zero as shown above.

Though somewhat tedious to show, the profit function is quasi-concave whenever the second derivative of profits with respect to traps/targets is negative[9]. The second derivative with respect to traps/targets is given below:

$$\frac{\partial^2 P_H}{\partial u^2}\left(\frac{\partial u}{\partial cm_{tt}}\right)^2+\frac{\partial P_H}{\partial u}\frac{\partial^2 u}{\partial {cm_{tt}}^2}<0\,.$$

While the second term is negative, the sign of the first term may be positive, and thus the sign of the entire term is indeterminate. Intuitively, for the term to be negative, an increase in mortality due to an increase in traps or targets must be decreasing at a sufficiently decreasing rate to more than offset the change in prevalence as mortality increases. Or, reductions in changes in mortality due to the last few traps/targets must be much lower than gains accruing to the first traps/targets. If this condition is not met, then the first-order conditions will then define a minimum.

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[9] The condition is based on the Hessian, and is explicitly derived in Appendix 2. We also note here that, if the only choice variable were the traps/target level, the matrix of second derivatives for the system of equations for both the non-cooperative game and the social optimum would equal zero, and whether or not the system was at a maximum would then depend on the sign of the second derivative.

Furthermore, consider an additional impact on overall prevalence due to a reduction in the fly densities as use of traps/targets increases. The first order condition with respect to traps and targets for the individual then becomes:

$$\frac{\partial \pi_i}{\partial cm_{tt-i}} = k_{OD}\left[\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{tt-i}} + \frac{\partial P_H}{\partial m}\frac{\partial m}{\partial cm_{tt-i}}\right]\left(1-k_{Tryp}\right)R_i = \overline{c}_{cm} \quad \textbf{[10]}$$

This differs from the FOC given in equation [4] only by the additional term, $\frac{\partial P_H}{\partial m}\frac{\partial m}{\partial cm_{tt-i}} > 0$. Clearly, the first order condition is greater when there is an additional impact on the fly densities; this is true for both the non-cooperative game and the social optimizer. Also, since the proportion healthy increases at an increasing rate as fly densities decrease, the second derivative is always greater when there is an additional impact on fly densities, and is thus more likely to be positive, all else equal.

We can now ask how the nature of the underlying epidemiology shapes individual incentives to adopt traps/targets. There are two aspects to the problem that complicate the evaluation of the externalities generated and thus the underlying incentive structure. First, the fact that the proportion of healthy cattle is bounded above at 1 means that we must consider corner solutions. Even if the profit function is everywhere concave, the game structure may be "fully privileged". This would mean that under the non-cooperative game, the unique equilibrium provision level is greater than or equal to that level for which the proportion healthy equals 1 (hereafter referred to as full provision). Because the socially optimal level of control is always greater than that under non-cooperation, the social optimum would also be at the corner solution of full provision. It is also possible that the social optimum is at the corner of full provision but the non-cooperative outcome is at interior solution below full provision, again because the social optimum is always greater than the non-cooperative solution. Finally, both the social optimum and non-cooperative outcomes may be at an interior level of provision below full provision. In these latter two cases, the underlying incentive structure can be characterized as a prisoner’s dilemma, where the unique equilibrium level of provision under the non-cooperative game is less than that arising under the social optimum. Thus, given that the profit function is concave, the underlying game structure might be characterized either as fully privileged or as a prisoner’s dilemma.

The second complication arises because the profit function may also be convex, at least over some range. In this case, there are many of possible game structures that might arise, including a “chicken game”, an assurance game, a prisoner’s dilemma, or a fully “not” privileged game. With sufficiently low costs of providing traps/targets, each individual will find it in his/her best interest to fully provide the traps/targets if the other person does not provide any, but is clearly better off if the other person fully provides traps/targets. In fact, the optimal amount for each person to provide is $CM_{tt}^{*} - \sum_{\substack{j=1 \\ j\neq i}}^{N} cm_{j-tt}$, where $CM_{tt}^{*}$ is that level of traps/targets such that $P_H\,(CM_{tt}^{*}) = 1$ and $\sum_{\substack{j=1 \\ j\neq i}}^{N} cm_{j-tt}$ is the total amount of the traps/targets provided by all other players besides player i. There are no gains to increasing $CM_{tt}$ above this level since benefits will not increase but costs will. The underlying incentive structure in this case resembles a chicken game. This means that if the other fully provides the $CM_{tt}^{*}$, then you prefer to provide 0, but if the other player puts on 0, you prefer to fully provide $CM_{tt}^{*}$. As costs increase, the individual would prefer not to provide any traps/targets if the other person does not do so, but, given increasing returns to scale, the person still does better at providing ½ $CM_{tt}^{*}$ when the other person provides ½ $CM_{tt}^{*}$, so that the underlying incentive structure resembles an assurance game. As costs increase still further, the individual's best response to the other person's provision level is always not to provide any traps/targets; that is no matter if the other person provides zero or ½ $CM_{tt}^{*}$ -- or anything in between – the first person's best response is to provide zero. As long as costs are not too high, however, the social optimum is still to fully provide the good, so that the underlying incentive structure is characterized by a prisoner's dilemma. Finally, costs can be high enough so that no provision is optimal for either the social optimizer or non-cooperating individuals.

The above results are quite interesting, but perhaps a bit difficult to visualize. In Figure 1, we illustrate two cases that may arise when profits are concave; the case where the social optimum is to fully provide traps/targets but where the non-cooperative game outcome leads to less than full provision, and the case where both the social optimal amount and the non-cooperative outcome are below full provision. To generate the graphs, we increase the constant marginal cost of the control method, which does not affect $P_H\left(CM_{tt}\right)$, meaning that full provision is reached at the same $CM_{tt}^{*}$ in every scenario, facilitating comparison across scenarios. The y-axis measures profits accruing to player 1, which are a function of the level of his/her control method provided, $cm_{tt-1}$, measured on the x-axis. Profits to player 1, however, also depend on the level of traps/targets provided by player 2, $cm_{tt-2}$. Thus, profit curves are generated under three different assumptions regarding the level of $cm_{tt-2}$: 1) $cm_{tt-2}$=0 for all levels of $cm_{tt-1}$, 2)

$cm_{tt-2}$= ½ $CM^*_{tt}$, which is equal to 75 for the parameters used to generate this graph[10], and 3) $cm_{tt-1}=cm_{tt-2}$. The line denoted as "Profits 1, $cm_{tt-2}$=0" gives the profits accruing to player 1 for different levels of $cm_{tt-1}$ assuming that player 2 does not provide any traps/targets; this curve captures the change in player 1's profits as he increases $cm_{tt-1}$ when player 2 is a free-riding. The line denoted as "Profits 1, $cm_{tt-2}$=½ $CM^*_{tt}$" captures the change in player 1's profits assuming that player 2 plays the social optimum. In a sense this curve gives the incentives of player 1 to cheat; the point where this curve takes a maximum along the relevant range is player 1's optimal response to $cm_{tt-2}$=75. Note, however, that the optimal response may well be $cm_{tt-1}$=75; in this case, incentives to cheat would be zero. The line denoted as "Profits, $cm_{tt-2}=cm_{tt-1}$", gives the profits accruing to player 1 assuming that both players always use the same amount of the control; this curve then represents returns from enforcing joint behavior as assumed under the social optimizer's problem. These three curves enable us to highlight incentives to cooperate, incentives to cheat, and incentives to not be taken advantage of by a free-rider. Finally, we generate these three curves for two different marginal cost levels; the solid line representing the lower marginal costs.

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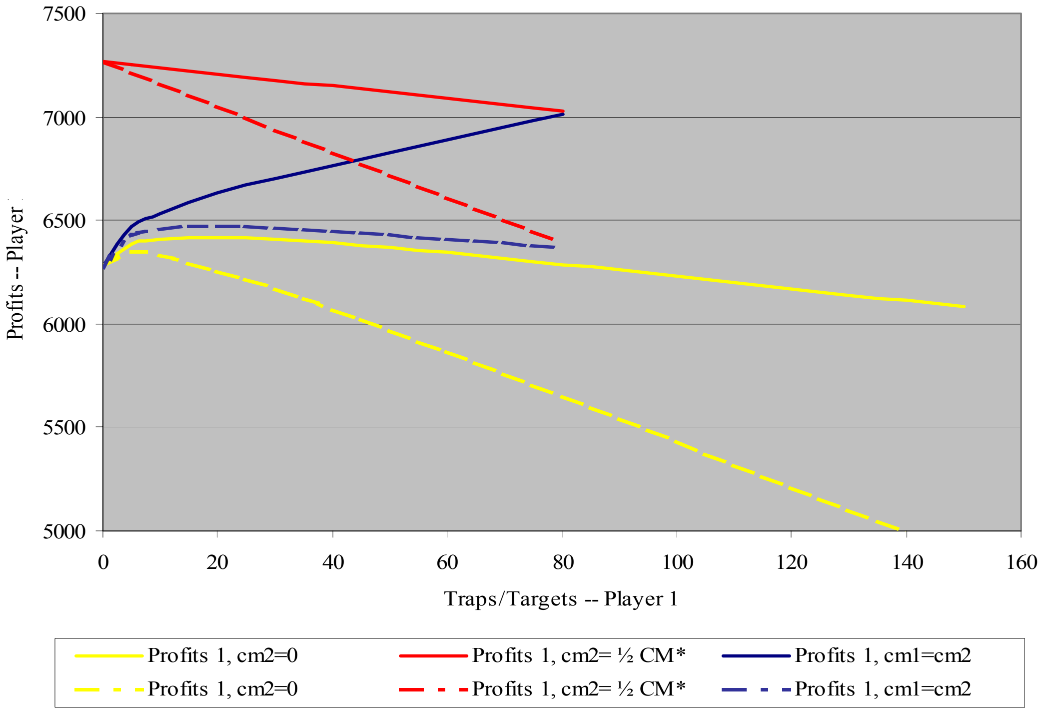
[10] With the exception of scenario 8, which is discussed more fully below.

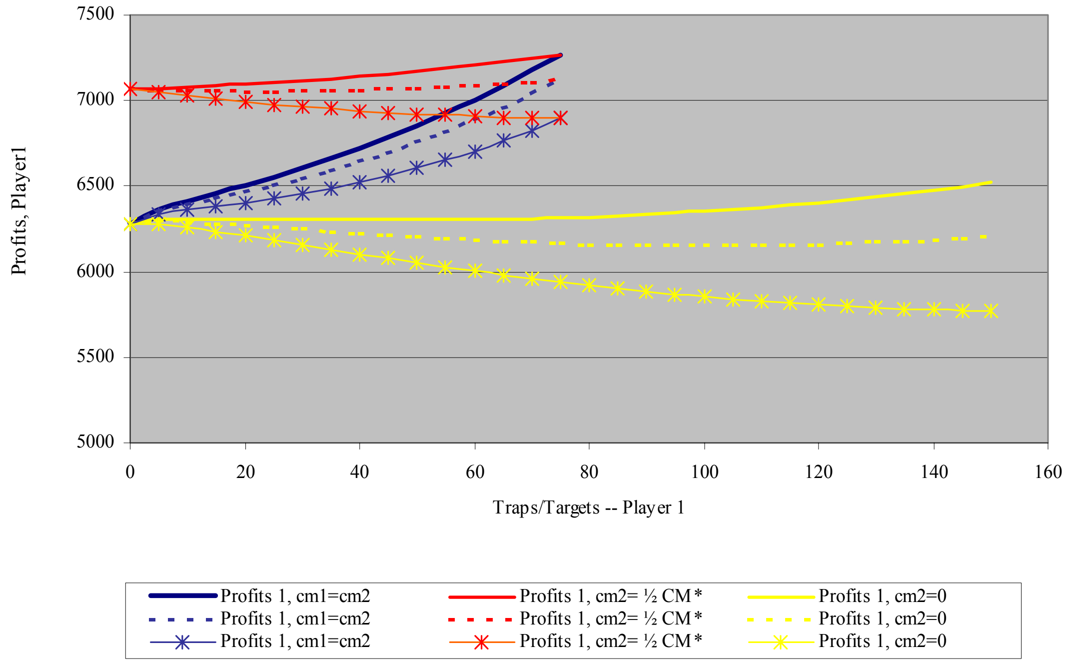
**Figure 1: Incentives to provide traps/targets; concave profit function**



Given the concave production function, incentives to free ride are everywhere decreasing the player 1's own provision level; in other words, if player 2 provide ½ $CM^*_{tt}$, the player 1's best response is to not provide any traps/targets; this is true for both of the costs levels illustrated above. Profits when player 2 does not provide any traps/targets are at first increasing and then decreasing; the maximum is reached at a lower level of $cm_{tt-1}$ in the higher cost case. Finally, profits from cooperating, i.e. when $cm_{tt-1} = cm_{tt-2}$, are also increasing $cm_{tt-1} + cm_{tt-2}$, but in the lower cost case, they are highest when $cm_{tt-1} = cm_{tt-2}$=75, whereas there is an internal solution of about 22 as costs increase.

Turning now to the case where the profit function is convex, Figure 2 plots each of the three incentives curves for three different marginal costs.

**Figure2: Incentives to provide traps/targets; convex profit function**



As in the previous figure, incentive lines shift downward as costs increase. Starting at very low marginal costs, the underlying incentive structure resembles a chicken game, where full provision is still the only equilibrium outcome. This result is captured in the fact that both the incentives to increase provision (red lines) and the incentives when player 2 does not provide any of the good (yellow lines) are strictly increasing, and take their maximum at the highest relevant $cm_{tt-1}$. As costs increase, the range of equilibria increase to encompass full provision, no provision, and any total provision level in between -- that is, an assurance game structure. Here, there are no incentives to free ride since profits when $cm_{tt-2}$=½ $CM^*_{tt}$, are highest when $cm_{tt-1}$=½ $CM^*_{tt}$, as before. However, there are no incentives to provide more when player 2 free rides, captured by the fact that the curve for $cm_{tt-2}$=0 takes a maximum at zero. Finally, as costs increase further still, both the curves for $cm_{tt-2}$=½ $CM^{*}_{tt}$ and for $cm_{tt-2}$=0 take a maximum at zero – indicating that there are both incentives to free ride and also incentives not to be taken advantage of (as when player 2 free rides); this means that the underlying game structure resembles a prisoner's dilemma. In this case, there will be no provision under the non-cooperative game. However, the social optimum is always to fully provide traps and targets as captured in the blue lines.

To conclude this section, we note that, because of the underlying epidemiology of trypanosomosis, there is a wide range of possible results under both a social optimum as well as under a non-cooperative game. If the profit function is concave, then provision of traps/targets will be lower when individuals do not cooperate except at a corner solution of full provision. With an interior solution and concave profit function, the underlying incentive structure resembles a prisoner's dilemma and there is a unique level of provision. If the profit function is convex, then the incentive structure underlying the non-cooperative game may take any form – resembling a chicken game, assurance game, or prisoner's dilemma.

It seems reasonable to assume that, under a chicken game structure, full provision should always result, but coordination might be important. Providing a public good where the underlying structure resembles an assurance game will be more costly than ensuring full provision under a chicken game structure, but should also be less costly than providing such a good when the underlying incentive structure resembles a prisoner's dilemma, all else equal (McCarthy et al., 2001). So, the question arises as to what conditions are more likely to lead to a fully privileged game than to a prisoner's dilemma. First, consider that the profit function is concave. Comparative statics give the highly intuitive results that a higher number of traps/targets will be maintained the lower are constant marginal costs, the greater is total revenue product, the lower are proportionate losses due to other diseases, the lower are proportionate losses due to other infections, the greater the marginal impact of traps/targets on mortality, and, for the most part, the greater is prevalence in the absence of any treatment[11]. On the other hand, when the profit function is convex, we are interested in changes in exogenous variables that shift the minimum towards the origin. The comparative statics are thus essentially the same; the Hessian is now positive, but we are evaluating changes that shift the minimum towards the origin. Thus, starting from very low costs and a chicken game structure, increasing costs causes the game structure to move to an assurance game, then to a prisoner's dilemma, and finally to a situation where neither the social optimizer nor the individuals provide any traps/targets. Similarly, starting from relatively high total revenue, decreasing total revenue leads to the same procession through the game structures, etc.

## 4. POUR-ONS

The basic model as developed above for traps and targets applies to pour-ons since the effect of this control method is also to increase tsetse mortality rates. However, in this case, there are also two direct impacts on the health of animals in the individual's own herd – the number of animals treated for trypanosomosis increases and the number of animals treated for other tick or biting fly transmitted diseases also increases. For simplicity, we assumed in section 2 above that all animals not treated become infected with other biting fly/tick diseases. The specification also implies that animals infected

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[11] Comparative static results are given in Appendix 2.

with tryps also suffer an additional loss due to other biting diseases. Using $cm_{po-i}$ to denote the use of pour-on by individual *i*, the maximization problem can be written a follows:

$$\max_{x_i, cm_{po-i}} \pi_i = \left[ T_i\left(cm_{po-i}\right) + k_{OD}\left(1 - T_i\left(cm_{po-i}\right)\right) * \left[ P_H\left(CM\right) + k_{Tryp}\left(1 - P_H\left(CM\right)\right)\right]\right] R_i\left(x_i\right) - \overline{c}_{cm} cm_{po-i} - \overline{c}_x x_i$$

$$s.t. P_H\left(CM_{po}\right) \leq 1; \quad T_i\left(cm_{po-i}\right) \leq 1;$$

The major difference with the traps and targets problem is that the proportion of treated animals is directly affected by the use of pour-ons. As with the case with traps and targets, there is also an additional impact on proportion of untreated animals that remain healthy, $P_H$, which is also a function of the level of pour-on use. First-order conditions for the individual are as follows:

$$\frac{\partial \pi_i}{\partial cm_{po-i}} = \left[\left[ k_{OD}\left(1 - T_i\right)\left(1 - k_{Tryp}\right)\left(\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{po-i}}\right)\right] + \left[\frac{\partial T_i}{\partial cm_{po-i}} * \left(1 - \left(k_{OD}\left(P_H + k_{Tryp}\left(1 - P_H\right)\right)\right)\right)\right]\right] * R_i - \overline{c}_{po} = 0 \quad [11]$$

$$\frac{\partial \pi_i}{\partial x_i} = \left[ T_i\left(cm_{po-i}\right) + k_{OD}\left(1 - T_i\left(cm_{po-i}\right)\right) * \left[ P_H\left(CM\right) + k_{Tryp}\left(1 - P_H\left(CM\right)\right)\right]\right] \frac{R_i\left(x_i\right)}{\partial x_i} - \overline{c}_x$$
[12]

We can now compare the first-order conditions for traps and targets vs. those for pour-ons under the non-cooperative game. Recall that the FOCs for traps and targets are as follows:

$$\frac{\partial \pi_i}{\partial cm_{tt-i}} = k_{od}\left[\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{tt-i}} * \left(1 - k_{Tryp}\right) * R_i\right] - \overline{c}_{cm} = 0 \quad [13]$$

$$\frac{\partial \pi_i}{\partial x_i} = \left[ k_{OD}\left[ P_H + k_{Tryp}\left(1 - P_H\right)\right]\right] * \frac{\partial R_i}{\partial x_i} - \overline{c}_x = 0 \qquad [14]$$

If the marginal cost of traps and targets were equal to marginal costs of pour-ons $\left(\overline{c}_{cm-tt} = \overline{c}_{cm-po}\right)$, and if tsetse mortality responded the same to both control methods

$\left(\frac{\partial u}{\partial cm_{po}}=\frac{\partial u}{\partial cm_{tt}}\right)$, then an individual would certainly prefer to use only pour-ons, because of the gains from animals treated for both trypanosomosis and other diseases; gains that accrue to the individual from the use of pour-ons that do not occur with the use of traps and targets (compare equations 11 and 13). However, it is not likely that either marginal costs or marginal reductions in mortality are likely to be the same for the two control methods; we return to this issue when we the conditions under which one control method would be preferred to another, in the discussion section below.

The social optimizer's problem may be written as:

$$\max_{x_i, cm_{po-i}} \pi_i = \sum\Big[T_i\left(cm_{po-i}\right)+k_{OD}\left(1-T_i\left(cm_{po-i}\right)\right)*\Big[P_H\left(CM\right)+k_{Tryp}\left(1-P_H\left(CM\right)\right)\Big]\Big]R_i\left(x_i\right)-\bar{c}_{cm}cm_{po-i}-\bar{c}_x x_i$$
$$s.t. P_H\left(CM_{po}\right)\leq 1; \quad T_i\left(cm_{po-i}\right)\leq 1;$$

With FOC's:

$$\frac{\partial \pi_i}{\partial cm_{po-i}}=\sum\left[\left[k_{OD}\left(1-T_{Trp}\right)*\left(\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial cm_{po-i}}\right)\right]+\left[\left(1-k_{OD}\right)\frac{\partial T_i}{\partial cm_{po-i}}*\left(P_H+k_{Tryp}\left(1-P_H\right)\right)\right]\right]*R_i-\bar{c}_{po}=0 \qquad [15]$$

$$\frac{\partial \pi_i}{\partial x_i}=\Big[T_i\left(cm_{po-i}\right)+k_{OD}\left(1-T_i\left(cm_{po-i}\right)\right)*\Big[P_H\left(CM\right)+k_{Tryp}\left(1-P_H\left(CM\right)\right)\Big]\Big]\frac{R_i\left(x_i\right)}{\partial x_i}-\bar{c}_x$$
[16]

Similar to the comparison of first-order conditions for traps and targets, we see that the FOC with respect to pour-ons is greater for the SO vs. NC when evaluating the expressions at the same $cm_i, x_i$ pair. Following a very similar proof to that shown in Appendix 1 for the case of traps/targets, it can easily be shown that pour-ons and head of livestock are both greater under the social optimum vs. the non-cooperative game outcome.

As with the case of examining traps and targets, the pour-on technology may also lead to convex production function; therefore, the same range of possible paired outcomes as with traps and targets may prevail so we do not repeat them here.

The multiplicity of possible scenarios makes comparing across the control methods difficult, but certain results can be highlighted. Clearly, the more important are other diseases, the more likely pour-ons will be preferred to traps or targets by either the social optimizer or a group of non-cooperating individuals. On the other hand, traps and targets may well be preferred by the social optimizer at the same time (or rather, under the same parameter values) that pour-ons are preferred by individuals operating under a non-cooperative game structure. This is more likely to be the case when $\left(\frac{\partial u}{\partial cm_{tt}} > \frac{\partial u}{\partial cm_{po}}\right)$, when $k_{Tryp} > k_{OD}$, and when the number of members is relatively large.

## 5. PREVENTATIVE AND CURATIVE DRUG USE

To begin, consider first how the proportion healthy $P_H$ changes with changes in *rinv*.

$$\frac{\partial P_H}{\partial rinv} = -\frac{e^{-uT}\varphi(ac+u)}{\left(e^{-uT}\varphi rinv + ac\right)^2} < 0 \qquad [17]$$

The second derivative is as follows:

$$\frac{\partial^2 P_H}{\partial (rinv)^2} = \frac{2\left(\left(e^{-uT}\varphi\right)^2 (ac+u)\right)}{\left(e^{-uT}\varphi rinv + ac\right)^3} > 0 \qquad [18]$$

It is important to remember that drug use will decrease the duration of infection in the animal that becomes sick, so that we will be interested in the change in percentage healthy as r-inv decreases. Given the relationships specified in equations 17 & 18, reducing the duration of infection increases the proportion healthy at an increasing rate. Whereas with traps, targets, and pour-ons, it is possible that the prevalence/ tsetse mortality relationship exhibits increasing marginal returns, with trypanocidal drugs the prevalence/infection duration relationship always exhibits increasing marginal returns. Nonetheless, whether or not the overall profit function is concave or convex will depend on the strength of $\frac{\partial^2 rinv}{\partial cm_D{}^2}$, where $cm_D$ is the trypanocidal drug control method.

Drugs also have a direct effect on the number of animals protected from tryps, but these treated animals will not be protected from other diseases. For simplicity, above we assumed that treated animals were simultaneously protected against tryps and other diseases, but here, we will consider that all animals lose the constant fraction, $k_{od}$ whether treated or not, so that $T_i$ refers to the proportion of treated animals that are protected from tryps only. Because the optimization problem is similar to those above, we simply provide the first-order conditions for the non-cooperative game below:

$$\frac{\partial \pi_i}{\partial cm_D} = \left[ k_{OD}\left[ (1-T_i)*(1-k_{Tryp})\left( \frac{\partial P_H}{\partial rinv}\frac{\partial rinv}{\partial cm_D} \right) \right] + \left[ \frac{\partial T_i}{\partial cm_D}*\left(1-\left(P_H + k_{Tryp}(1-P_H)\right)\right) \right] \right] * R_i - \bar{c}_{po} = 0 \quad [19]$$

$$\frac{\partial \pi_i}{\partial x_i} = k_{OD}\left[ T_i(cm_D) + \left(1-T_i(cm_D)\right)*\left[ P_H(CM) + k_{Tryp}\left(1-P_H(CM)\right) \right] \right] \frac{R_i(x_i)}{\partial x_i} - \bar{c}_x \quad [20]$$

Because curative drugs do not affect other diseases, equations [19] & [20] are lower than [11] & [12], all else equal. But, all else is not likely to be equal. As noted in the introduction, empirically, the impact of drugs on prevalence appears to be quite limited, so most of the value of drug use will be in shifting animals into the "treated" category. However, pour-ons have the same effect on treating against tryps but they also treat the same animals against other diseases, so that pour-ons should be preferred to preventative use of drugs, unless costs of drugs are much lower.

Next, consider curative use of drugs. In this case, one only spends the resources to treat an animal if that animal actually comes down with the tryps. In this case, all animals are susceptible, i.e. $T_i$=0.

$$\max_{x_i, cm_D} \pi_i = k_{OD}\left[\left[P_H\left(CM\right) + k_{Tryp}\left(1 - P_H\left(CM\right)\right)\right]\right] R_i\left(x_i\right) - \bar{c}_{cm} cm_D - \bar{c}_x x_i$$

$$s.t. P_H\left(CM_D\right) \leq 1$$

Taking the derivative with respect to curative drugs, and recalling that drugs will only be used on those animals becoming sick yields the following first-order:

$$\frac{\partial \pi_i}{\partial cm_D} = k_{OD}\left[\left[\left(1 - k_{Tryp}\right)\left(\frac{\partial P_H}{\partial rinv}\frac{\partial rinv}{\partial cm_D}\right)\right] + \left[1 - k_{Tryp}\right]\right] - \bar{c}_D = 0 \qquad [21]$$

To compare with preventative drug use, we rewrite the first-order condition in [19] above, substituting $\frac{\partial T_i}{\partial cm_D}$=1, we have the following

$$\frac{\partial \pi_i}{\partial cm_D} = \left[k_{OD}\left[\left(1 - T_i\right) * \left(1 - k_{Tryp}\right)\left(\frac{\partial P_H}{\partial rinv}\frac{\partial rinv}{\partial cm_D}\right)\right] + \left[\left(1 - \left(P_H + k_{Tryp}\left(1 - P_H\right)\right)\right)\right]\right] * R_i - \bar{c}_{po} = 0 \qquad [22]$$

Comparing the first terms in square brackets in each of the two equations, we note that $\left[\left(1 - k_{Tryp}\right)\left(\frac{\partial P_H}{\partial rinv}\frac{\partial rinv}{\partial cm_D}\right)\right] > \left[\left(1 - T_i\right) * \left(1 - k_{Tryp}\right)\left(\frac{\partial P_H}{\partial rinv}\frac{\partial rinv}{\partial cm_D}\right)\right]$. Similarly, comparing the terms in the second square brackets, we note that $\left[1 - k_{Tryp}\right] >$ $\left[\left(1 - \left(P_H + k_{Tryp}\left(1 - P_H\right)\right)\right)\right]$. Thus, the first-order condition with respect to drug use is greater for preventative vs. curative use, and thus, given the choice – and the assumptions we have made – farmers will always prefer curative drug use to preventative drug use.

Also, the lower the prevalence, the more valuable it is not to treat until the animal becomes sick – and thus the more likely curative drug use will be preferred to pour-ons. Again, however, this would be more likely in areas where other diseases were of minor importance.

A major assumption in the above model is that any infection is immediately diagnosed and can be treated immediately. If there is a probability that a correct diagnosis won't be made and/or that drugs will not be available when needed, then clearly expected marginal benefits of waiting to cure will be reduced. Thus, to the extent that diagnosis and access to drugs are unreliable, preventative drug use becomes more attractive.

## 6. NON-COOPERATION IN STOCKING DENSITIES AND CONTROL METHOD LEVELS:

### 6.1 CONCAVE CONTROL METHOD FUNCTION:

Above, we have assumed that livestock production is a function of the individual's own herd size only. This assumption might reflect a situation where stocking rates are relatively light, where animals are kept on private fields and/or grass is cut and carried. In the following section, we relax this assumption and allow for a non-cooperative game to be played over grazing on common pasture, as well in the provision of a pure public good. We first consider the case where returns to the control method are concave, i.e. $\frac{\partial^2 P_H}{\partial u^2}\left(\frac{\partial u}{\partial cm}\right)^2 + \frac{\partial P_H}{\partial u}\frac{\partial^2 u}{\partial cm^2} < 0$, and then consider the case where returns are convex.

To highlight the interdependency of livestock production on common-pool pastures, we use a standard representation for the total product function:

$TP_i(X) = x_i f\left(x_i, \sum_{j \neq i} x_j\right)$, Where $f\left(x_i, \sum_{j \neq i} x_j\right)$ is the average product function. To simplify notation, we let $X_j = \sum_{j \neq i} x_j$, so that $TP_i(X) = x_i f(x_i, X_j)$; when convenient and clear, we simply use $f$ in place of $f(x_i, X_j)$ We assume that the total product function is concave, which implies that the derivative of the average product function is negative, $\frac{\partial f(x_i, X_j)}{\partial x_i} < 0$.

We consider only the use of traps/targets in mathematical detail since, with this control method, we may let $T_i$=0 thereby considerably simplifying notation. In this case, the individual's maximization problem is written as follows:

$$\max \pi_i = \left(P_H(CM_{tt}) + k\left(1 - P_H(CM_{tt})\right)\right) * x_i f(x_i, X_j) - \overline{c}_{CM} cm_{tt-i} - \overline{c}_x x_i$$

$$s.t. P_H(CM_{tt}) \leq 1$$

$$\frac{\partial \pi_i}{\partial T} = \frac{\partial P_H}{\partial u} \frac{\partial u}{\partial T}\left((1-k)TP_i\right) - \overline{c}_{CM} = 0$$

$$\frac{\partial \pi_i}{\partial x_i} = \left(P_H(CM_{tt}) + k\left(1 - P_H(CM_{tt})\right)\right)\left(f + x_i \frac{\partial f}{\partial x}\right) - \overline{c}_x = 0$$

$$\forall i$$

The SO problem may be re-written as:

$$\max \sum \pi_i = \sum \left(P_H(CM_{tt}) + k\left(1 - P_H(CM_{tt})\right)\right) * x_i f(x_i, X_j) - \sum \overline{c}_{CM} cm_{tt-i} - \sum \overline{c}_x x_i$$

$$s.t. P_H(CM_{tt}) \le 1$$

$$\frac{\partial \pi_i}{\partial t_i} = \sum_i \frac{\partial P_H}{\partial u}\frac{\partial u}{\partial T}\left(\left(1-k\right)x_i f\left(x_i, X_j\right)\right) - \overline{c}_{CM} = 0$$

$$\frac{\partial \pi_i}{\partial x_i} = \left(P_H\left(CM_{tt}\right) + k\left(1 - P_H\left(CM_{tt}\right)\right)\right)\left(f + x_i\frac{\partial f}{\partial x_i} + \sum_{j \ne i} x_j \frac{\partial f}{\partial x_i}\right) - \overline{c}_x = 0$$

$$\forall i$$

We note that the first-order conditions for both the social optimizer and the individual with respect to the control method are the same as in the previous section. It can easily be shown that $P_H{}^{SO} > P_H{}^{NC}$ in this extended problem, since there is no combination, $x_i{}^{NC}$, $x_i{}^{SO}$, for which both $x_i f\left(x_i, X_j\right) > \sum x_i f\left(x_i, X_j\right)$ and $\left(f + \frac{\partial f}{\partial x_i} + \sum_{j \ne i} \frac{\partial f}{\partial x_j}\right) > \left(f + \frac{\partial f}{\partial x_i}\right)$ hold simultaneously[12].

Defining $\phi^{SO} = P_H{}^{SO} + k\left(1 - P_H{}^{SO}\right)$, $\phi^{NC} = P_H{}^{NC} + k\left(1 - P_H{}^{NC}\right)$ and substituting this notation, we can rewrite the first-order conditions for NC and SO with respect to $x_i$ as follows:

$$\frac{\partial \pi_i{}^{NC}}{\partial x_i} = \phi^{NC}\left(f + x_i\frac{\partial f}{\partial x}\right) - \overline{c}_x = 0$$

$$\frac{\partial \pi_i{}^{SO}}{\partial x_i} = \phi^{SO}\left(f + x_i\frac{\partial f}{\partial x_i} + \sum_{j \ne i} x_j \frac{\partial f}{\partial x_j}\right) - \overline{c}_x = 0$$

If $\phi^{NC} = \phi^{SO}$, then $x_i{}^{NC} > x_i{}^{SO}$, since $\left(f + x_i\frac{\partial f}{\partial x_i} + \sum_{j \ne i} x_j \frac{\partial f}{\partial x_j}\right) < \left(f + x_i\frac{\partial f}{\partial x_i}\right)$ at the same $x_i$, which is the standard result of over-exploitation. However, in

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[12] Proof provided in Appendix 4.

equilibrium $\phi^{NC} < \phi^{SO}$, which implies that $x_i^{NC} >=< x_i^{SO}$. The intuition is that the lower provision of the control method under non-cooperation may sufficiently lower profits (and marginal profits) so that fewer animals will be stocked despite the tendency to overstock induced by the negative externality in grazing.

Overstocking results if:

$$\frac{\left(f + x_i \dfrac{\partial f}{\partial x_i}\right)^{NC}}{\left(f + x_i \dfrac{\partial f}{\partial x_i} + \sum_{j \neq i} x_j \dfrac{\partial f}{\partial x_j}\right)^{SO}} > \frac{\phi^{SO}}{\phi^{NC}}$$, when the expression is evaluated at the same

$x_i, cm_{tt-i}$ pair.

Overstocking is more likely to result when both the difference between the control method provision levels, $\phi^{SO} - \phi^{NC}$, is relatively small, and optimal provision under the social optimum is relatively high. It can also be shown that overstocking is more likely to result the greater is the negative externality, and the larger the number of players.

To summarize this sub-section, and recalling that we have assumed that returns to the control method are concave, health inputs will always be lower when there is also non-cooperation in stock densities. This is an important result that must be considered in communities where members rely on un-managed common pastures because incentives to adopt and/or increase provision of control measures will be lower.

## 6.2 CONVEX CONTROL METHODS FUNCTION:

When the control method function is convex, there are three possible paired provision outcomes – both provide full provision, the social optimizer fully provides the control method but the non-cooperative outcome is to provide no control measures, and neither provide any control measures.

If both provide the same level of the control measure – either fully or none at all – then stock densities will be higher and profits will be lower under non-cooperation. Mirroring the results from the section immediately above, if the social optimizer fully provides the control measure but the non-cooperative outcome is to provide none, then stock densities under non-cooperation may be equal, greater than or less than those obtaining at the social optimum.

Nonetheless, the lower is the total product, the less likely it is that full provision will be chosen. To the extent that total profits are lower under non-cooperation, the less likely it will be that full provision is chosen, and the more likely it is that the incentive structure underlying the choice of provision levels will resemble a prisoner's dilemma type game, as discussed above.

## 7. DISCUSSION

As captured in the plethora of possible scenarios presented above, the technical relationship between a control method and the response in prevalence is an empirical question. However, we can still characterize under which conditions individuals are likely to provide and maintain traps/targets, or rather to use pour-ons or trypanocidal drugs. Assuming that a community can without cost enforce the social optimum, the use of traps alone is more likely to occur when costs of pour-ons are very high, when the decrease in productivity resulting from non-trypanosomosis diseases is not very great (so other diseases that could potentially be treated with pour-ons are not very important), and when the marginal increase in tsetse mortality due to an increase in pour-ons is much smaller than the marginal reduction with traps and targets. Using only pour-ons is more likely to be optimal when the decrease in productivity resulting from tryps is low compared to the decrease in productivity from other diseases, and when costs of maintaining traps are high.

However, given non-cooperation in the provision of the public good, use of pour-ons becomes much more attractive. Even if there is only a slight impact of pour-ons on overall prevalence of tryps, as long as private returns are relatively high (other diseases important, gains in own productivity are relatively large (i.e. $k_{OD}$ is relatively small)), then only pour-ons will be provided under a non-cooperative game. Furthermore, as the number of members increases, it is even more likely that the social optimizer will prefer traps and targets. As discussed in Brightwell et al. (2001), in the case where many members will benefit, a centralized authority for providing the traps and targets becomes essential – though community members themselves must recognize the benefits and support the goals of the centralized institution.

Non-cooperation in the number of animals to stock, e.g. if community members rely heavily on un-managed or imperfectly managed common property pastures as a source of forage for the animals, reduces the incentives to provide either pour-ons or traps and targets. The marginal returns to any health input decrease with lower forage/feed productivity. There has been some discussion as to the appropriate institutional structure of tsetse control programs in the semi-arid regions in East Africa; but to the extent that *per animal* productivity is lower, any type of control program is likely to face more difficulty in developing a sustainable community-based structure for maintenance – and it is quite possible in these areas that no provision is optimal even under a social optimum.

Curative drug use may very well be the optimal and unique control strategy. This is more likely to be true when: prevalence of tryps itself is quite low, prevalence of other non-tryps diseases is relatively low, there is an additional negative impact on prevalence from curative drug use, pastures are private and/or there is little over-exploitation of common pool pastures, and cost of drugs is relatively low.

No control of any kind is likely to be optimal when returns to animal production per se are relatively low. Very low returns may be realized when there is a lot of overstocking and when output prices are low.

Now that we’ve reached the end of the discussion, it may seem that we have gone to a lot of trouble simply to verify what ought to have been common knowledge beforehand. In fact, however, the incentive problems associated with the provision of alternative tsetse control methods are still probably not well enough appreciated. While many experts view the provision of traps quite skeptically (c.f. Leak, 1998), another group believes that all one has to do is to get across to community members that providing traps is good for everyone (c.f. the discussion of this in Brightwell, et al. 2001). That is to say, many believe that the reason traps and targets have failed in the past is because the weren’t “owned” by the community, that community participation was lacking, and that the top-down approach meant that traps and targets were likely to dilapidate rather quickly once project leaders and/or funding was stopped. But, here we have shown that it is quite possible that the incentive structure to provide the traps and targets is akin to a prisoner’s dilemma, and so it is likely to be very costly for community members to provide such a good. More importantly, it will be even more costly – if not impossible – for a community to provide traps and targets when community members also rely on un-managed common pastures as the major feed source. Despite much discussion of "devolution" and privatization of services, it appears as if this is one public good that simply might be better provided at a more centralized level. Particularly in areas prone to sleeping sickness epidemics, a real question can be asked why individuals in a community ought to provide the good, and why it shouldn't be an activity undertaken by the government (local and/or national).

## 8. CONCLUSION

As noted above, because of the many possible outcomes, empirical data to baseline model parameters is really necessary. Authors of this paper are currently involved in a large field project whose aim is to collect data with which to baseline such a model. A number of empirical complications also need to be modeled. For instance, a relatively straightforward extension could be made to allow for negative environmental impacts stemming from pour-ons or sprays, though these impacts are not yet fully understood let alone quantified (Kisamba-Mugerwe, personal communication). The impact of drug resistance on current proportion of healthy animals can be included in a straightforward way, but obviously dynamic implications would require a dynamic model. Though there is evidence of serious drug resistance in other countries, to date, there is little evidence of such resistance in southeast Uganda. The potential for re-invasion of tsetse from outside the geographical area under consideration must also be included in the model; this too will vary across our study area and awaits empirical information.

Despite these complications, however, the essential result of the paper is that a comparison across control measures must be made not only in terms of the breakdown between private and public benefits but also in terms of the incentive structure underlying the provision of each control method. Those involved in tsetse and trypanosomosis control seem to overwhelmingly favor traps/targets because, without considering underlying individual incentive structures to cooperate or not cooperate over their provision, these appear to have the largest impact on prevalence with the lowest cost. Currently, it is fashionable to ascribe past failures with traps/targets to the lack of "true" community participation. It is certainly true that, in the past, many veterinary health measures and projects were imposed from above with little input by communities who were then expected to adopt these measures. Nonetheless, it is quite possible that the pure public goods nature of traps and targets, combined with an underlying incentive structure that may resemble a prisoner's dilemma, is not only an important part of the explanation for past failures, but it also indicates that future failures – even with bottom-up participatory approaches – may not work either.

Finally, while tsetse and trypanosomosis control has been the empirical focus of this paper, the theoretical model developed above should be of interest more generally. As national governments continue to devolve responsibility for provision of goods and services with large public goods aspects – including pest management and vector-borne disease control – the epidemiology-economic framework developed here can be applied to analyze the likely adoption of alternative strategies and the resultant impact on household welfare.  Even without the epidemiology component, the economic framework for analyzing individual incentives for public goods provision – including interactions among several choices characterized by interdependencies in production – provides interesting insight into the provision decision, and may allow policymakers to better decide the level at which responsibility for public goods provision should be devolved.

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## APPENDIX 1--COMPARISON OF NON-COOPERATIVE OUTCOME VS. SOCIAL OPTIMUM WHEN THE SYSTEM IS QUASI-CONCAVE

The proof below shows that of $cm_{tt-i}^{SO} > cm_{tt-i}^{NC}$ and $x_i^{SO} > x_i^{NC}$ when the profit function is concave.

It is easiest to re-write the social optimizer's problem as the following:

$$\max_{CM,x_i} = \sum\left[k_{OD}\left[T_i+\left(1-T_i\right)*\left[P_H\left(CM_{tt}\right)+k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right]\right]*R_i\right]-\overline{c}_{cm}CM-N\overline{c}_x x_i=0$$

We assume that the social optimizer chooses $CM$ , and subsequently enforces purchase of $\frac{CM}{N}$ by each producer, which is done to simplify the proof.

To simplify notation, let

$$k_{OD}\left[T_i+\left(1-T_i\right)*\left[P_H\left(CM_{tt}\right)+k_{Tryp}\left(1-P_H\left(CM_{tt}\right)\right)\right]\right]=\left[H+k_{Tryp}S\right],$$

$$\frac{\partial P_h}{\partial u}\frac{\partial u}{\partial CM}=MP_{CM} \quad \text{and} \quad \frac{\partial R_i}{\partial x_i}=MP_{x_i}$$

First order conditions can then be re-written as:

$$\frac{\partial\sum\pi_i}{\partial CM}=N\left(1-T_i\right)\left(1-k_{Tryp}\right)MP_{CM}*R_{\ i}=\overline{c}_{cm}$$

$$\frac{\partial\sum\pi_i}{\partial x_i}=\left(H+k_{Tryp}S\right)MP_{x_i}=\overline{c}_x,\ \forall i$$

In appendix 1, we presented the Hessian for the four equation non-cooperative game, and so do not develop the same for the social optimum particularly because we are interested here in showing the results assuming that the Hessian is positive semi-definate. First, we examine the cross-partials of the FOC's with respect to N:

$$\frac{\partial\sum\pi_i}{\partial CM\,\partial N}=\left(1-T_i\right)\left(1-k_{Tryp}\right)MP_{CM}*R_{\ i}>0$$

$$\frac{\partial\sum\pi_i}{\partial x_i\partial N}=\frac{\partial\left(H+k_{Tryp}S\right)}{\partial N}MP_{x_i}=\overline{c}_x,\ \forall i$$

Consider the two-player case:

$$\frac{dCM}{dN} = \frac{\begin{vmatrix} -\dfrac{\partial\sum\pi_i}{\partial CM\,\partial N} & \dfrac{\partial\sum\pi_i}{\partial CM\,\partial x} \\ -\dfrac{\partial\sum\pi_i}{\partial x_i\partial N} & \dfrac{\partial^2\sum\pi_i}{\partial x_i^2} \end{vmatrix}}{|H|}$$

which is clearly greater than zero, as long as |H|>0.

Similarly,

$$\frac{dx_i}{dN} = \frac{\begin{vmatrix} \dfrac{\partial^2\sum\pi_i}{\partial CM^2} & -\dfrac{\partial\sum\pi_i}{\partial CM\,\partial N} \\ \dfrac{\partial\sum\pi_i}{\partial x_i\partial CM} & -\dfrac{\partial\sum\pi_i}{\partial x_i\,\partial N} \end{vmatrix}}{|H|}$$

which is also clearly greater than zero, as long as |H|>0.

Since, $R_i$ is not a function of $\sum_{j\neq i} x_j$, then these results hold when one expands to consider more than two players. We note here that $cm_i^{SO}$ may not increase with increases in *N*, given diminishing returns to the disease control production function. However, $CM^{SO} > CM^{NC}$, so that $cm_{tt-i}^{SO} > cm_{tt-i}^{NC}$ and $x_i^{SO} > x_i^{NC}$.

# APPENDIX 2: SECOND-ORDER CONDITIONS AND COMPARATIVE STATIS, 2 PLAYERS

Here, we derive second-order conditions for the simplest case for traps and targets, where the only impact is on mortality. Similar results when we consider additional pure public goods impacts (e.g. on fly density), and when we consider control methods that yield private benefits, though the comparative statics are significantly more complex. Below, we present results for the simplest case, additional proofs can be obtained from the authors upon request.

Though we have a system of four equations and four variables, $cm_{tt-1}, cm_{tt-2}$, $x_{1,} x_2$, because the public good is a pure public good, the Hessian, though negative semi-definate, is equal to zero. The pure public good's nature of the problem means that individual contributions are not well-defined, but rather only the total amount of the good provided. As we show below, the system to be evaluated can be reduced to two equations in two unknowns: $CM_{tt}, x_i$. We begin by looking at the presenting the second derivatives:

$$\frac{\partial^2 \pi_1}{\partial {cm_{tt-1}}^2} = \left[ \frac{\partial^2 P_H}{\partial u^2} \left( \frac{\partial u}{\partial cm_{tt-1}} \right)^2 + \frac{\partial P_H}{\partial u} \frac{\partial^2 u}{\partial {cm_{tt-1}}^2} \right] (1 - k_{Tryp}) R_1 \qquad \text{[A1]}$$

$$\frac{\partial^2 \pi_1}{\partial cm_{tt-1} \partial x_1} = \frac{\partial P_H}{\partial u} \frac{\partial u}{\partial cm_{tt-1}} (1 - k_{Tryp}) \frac{\partial R_1}{\partial x_1} \qquad \text{[A2]}$$

$$\frac{\partial^2 \pi_1}{\partial cm_{tt-1} \partial cm_{tt-2}} = \left[ \frac{\partial^2 P_H}{\partial u^2} \left( \frac{\partial u}{\partial cm_{tt-1}} \frac{\partial u}{\partial cm_{tt-2}} \right) + \frac{\partial P_H}{\partial u} \frac{\partial^2 u}{\partial cm_{tt-1} \partial cm_{tt-2}} \right] (1 - k_{Tryp}) R_1 \qquad \text{[A3]}$$

$$\frac{\partial^2 \pi_1}{\partial cm_{tt-1} \partial x_2} = 0 \qquad [A4]$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial cm_{tt-1}} = \frac{\partial P_H}{\partial u} \frac{\partial u}{\partial cm_{tt-1}} \left(1 - k_{Tryp}\right) \frac{\partial R_1}{\partial x_1} \qquad [A5]$$

$$\frac{\partial^2 \pi_1}{\partial x_1{}^2} = \left[H + k_{Tryp} S\right] \frac{\partial^2 R_1}{\partial x_1{}^2} \qquad [A6]$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial cm_{tt-2}} = \frac{\partial P_H}{\partial u} \frac{\partial u}{\partial cm_{tt-2}} \left(1 - k_{Tryp}\right) \frac{\partial R_1}{\partial x_1} \qquad [A7]$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial x_2} = 0 \qquad [A8]$$

And similarly for player 2:

Given the pure public good nature of traps/targets, $\frac{\partial P_H}{\partial u} \frac{\partial u}{\partial cm_{tt-1}} = \frac{\partial P_H}{\partial u} \frac{\partial u}{\partial cm_{tt-2}}$, and

$$\frac{\partial^2 P_H}{\partial u^2} \left( \frac{\partial u}{\partial cm_{tt-1}} \right)^2 \frac{\partial P_H}{\partial u} \frac{\partial^2 u}{\partial cm_{tt-1}{}^2} = \left[ \frac{\partial^2 P_H}{\partial u^2} \left( \frac{\partial u}{\partial cm_{tt-1}} \frac{\partial u}{\partial cm_{tt-2}} \right) + \frac{\partial P_H}{\partial u} \frac{\partial^2 u}{\partial cm_{tt-1} \partial cm_{tt-2}} \right] = \frac{\partial^2 P_H}{\partial u^2} \left( \frac{\partial u}{\partial cm_{tt-2}} \right)^2 \frac{\partial P_H}{\partial u} \frac{\partial^2 u}{\partial cm_{tt-2}{}^2}$$

Also, recall that players are homogeneous, so that $\frac{\partial R_1}{\partial x_1} = \frac{\partial R_2}{\partial x_2}$ and $\frac{\partial^2 R_1}{\partial x_1{}^2} = \frac{\partial^2 R_2}{\partial x_2{}^2}$.

Finally, similarly to other two-input production functions, we assume that the product of own derivatives is greater than the product of the cross partials, or

$$\frac{\partial^2 \pi_1}{\partial x_1{}^2} \frac{\partial^2 \pi_1}{\partial cm_{tt-1}{}^2} > \frac{\partial^2 \pi_1}{\partial x_1 \partial cm_{tt-1}} \frac{\partial^2 \pi_1}{\partial cm_{tt-1} \partial x_1}.$$

Let A=[A1], [A3] ; B=[A2], [A5],[A7]; C=[A6]. We can then write the Hessian as follows:

$$H=\begin{vmatrix} A & B & A & 0 \\ B & C & B & 0 \\ A & 0 & A & B \\ B & 0 & B & C \end{vmatrix}$$

Where:

$A<0$
$AC-B^2>0$

$$A[AC] + B[AB-BA] + A[-AC] = 0$$

$[2AC+2B^2][AC-B^2]=0$

So H is indeed negative semi-definite. The first and third rows are clearly linearly dependent, as are the second and fourth rows. Since we only know the total amount of the good provided in equilibrium, we need only examine the changes in the individual's first-order conditions for a change in the total amount provided and his/her own choice of animals. We thus using the following:

$$H=\begin{vmatrix} A & B \\ B & C \end{vmatrix}, \text{ since } \frac{\partial CM_{tt}}{\partial cm_{i-tt}}=1.$$

Next, we consider changes costs of traps $\left(\overline{c}_{tt}\right)$, costs of the animals $\left(\overline{c}_{x}\right)$, the losses sustained when animals get sick $\left(k_{Tryp}\right)$, and changes in parameters that increase the underlying disease prevalence, for instance the probability of a fly becoming infected from an infected cow $(b)$. The latter characteristics (those affecting equilibrium prevalence in the absence of treatment) may differ across agro-ecologic zones and by types of tsetse flies, for instance.

For a change in the cost of tsetse traps, we note that:

$$\frac{\partial^2 \pi_1}{\partial CM_{tt} \partial \overline{c}_{tt}} = -1 < 0$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial \overline{c}_{tt}} = 0 > 0$$

$$\frac{dCM_{tt}}{d\overline{c}_{tt}} = \frac{\begin{vmatrix} 1 & B \\ 0 & C \end{vmatrix}}{|H|} = \frac{C}{|H|} < 0$$

$$\frac{dx_i}{d\overline{c}_{tt}} = \frac{\begin{vmatrix} A & 1 \\ B & 0 \end{vmatrix}}{|H|} = \frac{-B}{|H|} < 0$$

And similarly, for a change in the cost of animals:

$$\frac{\partial^2 \pi_1}{\partial CM_{tt} \partial \overline{c}_{x}} = 0 < 0$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial \overline{c}_{x}} = -1 > 0$$

$$\frac{dCM_{tt}}{d\overline{c}_{x}} = \frac{\begin{vmatrix} 0 & B \\ 1 & C \end{vmatrix}}{|H|} = \frac{-B}{|H|} < 0$$

$$\frac{dx_i}{d\overline{c}_{x}} = \frac{\begin{vmatrix} 1 & B \\ 0 & C \end{vmatrix}}{|H|} = \frac{C}{|H|} < 0$$

For a change in the proportionate losses when sick, we note that:

$$\frac{\partial^2 \pi_1}{\partial CM_{tt}\partial k_{Tryp}} = -\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial CM_{tt}} R < 0$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial k_{Tryp}} = \left[1 - P_H\right]\frac{\partial R}{\partial x} > 0$$

$$\frac{dCM_{tt}}{dk_{Tryp}} = \frac{\begin{vmatrix} \frac{\partial P_H}{\partial u}\frac{\partial u}{\partial CM_{tt}} R & B \\ -\left[1-P_H\right]\frac{\partial R}{\partial x} & C \end{vmatrix}}{|H|} = \frac{\overbrace{\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial CM_{tt}} R * C}^{-} + \overbrace{\left[1-P_H\right]\frac{\partial R}{\partial x} * B}^{+}}{|H|} <=> 0$$

$$\frac{dx_i}{dk_{Tryp}} = \frac{\begin{vmatrix} A & \frac{\partial P_H}{\partial u}\frac{\partial u}{\partial CM_{tt}} R \\ B & -\left[1-P_H\right]\frac{\partial R}{\partial x} \end{vmatrix}}{|H|} = \frac{\overbrace{-\left[1-P_H\right]\frac{\partial R}{\partial x} * A}^{+} - \overbrace{\frac{\partial P_H}{\partial u}\frac{\partial u}{\partial CM_{tt}} R * B}^{+}}{|H|} <=> 0$$

Thus, the number of animals increases unambiguously. The impact on traps/targets is ambiguous; decreasing proportionate losses decreases the marginal benefits of traps/targets holding livestock constant, but increasing the number of livestock increasing benefits since the inputs are gross compliments.

Finally, we consider a change in the underlying prevalence of the disease, for instance, a change in the probability that fly becomes infected after feeding on an infected cow, which is the parameter *b* from the epidemiological model. After some algebraic manipulation, it can be shown that $\frac{\partial P_H}{\partial b} < 0$, and $\frac{\partial^2 P_H}{\partial u \partial b} > 0$ . In which case:

$$\frac{\partial^2 \pi_1}{\partial CM_{tt}\partial b} = \frac{\partial^2 P_H}{\partial u \partial b}\frac{\partial u}{\partial CM_{tt}}\left(1 - k_{Tryp}\right) R > 0$$

$$\frac{\partial^2 \pi_1}{\partial x_1 \partial b} = \frac{\partial P_H}{\partial b}\left(1-k_{Tryp}\right)\frac{\partial R}{\partial x} < 0$$

$$\frac{dCM_{tt}}{db} = \frac{\begin{vmatrix} -\frac{\partial^2 P_H}{\partial u \partial b}\frac{\partial u}{\partial CM_{tt}}\left(1-k_{Tryp}\right)R & B \\ -\frac{\partial P_H}{\partial b}\left(1-k_{Tryp}\right)\frac{\partial R}{\partial x} & C \end{vmatrix}}{|H|} = \frac{\overbrace{-\frac{\partial^2 P_H}{\partial u \partial b}\frac{\partial u}{\partial CM_{tt}}\left(1-k_{Tryp}\right)R * C}^{+} + \overbrace{\frac{\partial P_H}{\partial b}\left(1-k_{Tryp}\right)\frac{\partial R}{\partial x} * B}^{-}}{|H|} \text{ <=> } 0$$

$$\frac{dx_i}{db} = \frac{\begin{vmatrix} A & -\frac{\partial^2 P_H}{\partial u \partial b}\frac{\partial u}{\partial CM_{tt}}\left(1-k_{Tryp}\right)R \\ B & -\frac{\partial P_H}{\partial b}\left(1-k_{Tryp}\right)\frac{\partial R}{\partial x} \end{vmatrix}}{|H|} = \frac{\overbrace{-\frac{\partial P_H}{\partial b}\left(1-k_{Tryp}\right)\frac{\partial R}{\partial x} * A}^{-} + \overbrace{\frac{\partial^2 P_H}{\partial u \partial b}\frac{\partial u}{\partial CM_{tt}}\left(1-k_{Tryp}\right)R * B}^{+}}{|H|} \text{ <=> } 0$$

In this case, the impact is ambiguous for both inputs. The direct effect is to increase the marginal benefits from setting traps/targets and thus to increase traps/targets, though marginal benefits from animals decreases for a given level of traps/targets.

If

After some manipulation, it can be shown that $\frac{\partial P_H}{\partial b} < 0$, and $\frac{\partial^2 P_H}{\partial u \partial b} > 0$ . In this case, we can examine the following equations:

# APPENDIX 3--FUNCTIONAL FORMS AND PARAMETER VALUES USED IN THE SIMULATION MODEL

The impact of control methods on tsetse mortality is modeled as an exponential function, and specified as follows:

$$u = \overline{u}_0 + \delta_{cm}\left(cm_{k-1} + cm_{k-2}\right)^{\gamma_{cm}}$$

where $u$ is the tsetse mortality rate, $k$ denotes the control methods that affect tsetse mortality (in our case, targets/traps and pour-ons), $\overline{u}_0$ is the baseline mortality rate that obtains when no control method is used, and $\delta_{cm}, \gamma_{cm}$ are the parameters that determine the shape of the "increased mortality" production function. All parameters are assumed to be positive. Also, the same functional form is used for both traps/targets and pour-ons to capture the impact on mortality, though parameter values, $\delta_{cm}, \gamma_{cm}$, differ depending on the control method used.

Similarly, the impact of the control method on fly densities is modeled as:

$$m = \overline{m} * \left(1 - \lambda_{cm}\left(cm_{k-1} + cm_{k-2}\right)^{\varpi_{cm}}\right)$$

where $m$ is fly density, $k$ denotes the control methods that affect fly density (targets/traps and pour-ons), $\overline{m}$ is fly densities occurring in the absence of control measures, and $\lambda_{cm}, \varpi_{cm}$ determine the shape of the $m$ -production function.

And:

$$rinv = \overline{rinv} * \left(1 - \tau_{cm}\left(cm_{k-1} + cm_{k-2}\right)^{\psi_{cm}}\right)$$

where $rinv$ is duration of infection, $k$ denotes the control methods that affect duration of infection (drugs), $\overline{rinv}$ is duration of infection in the absence of control measures, and $\tau_{cm}, \psi_{cm}$ determine the shape of the $rinv$-production function.

These equations are then substituted into the expression, $R_0 = \frac{e^{-uT}}{u} * \frac{ca^2bm}{r}$, and

$$P_H = \frac{\frac{ac}{u} + 1}{R_0 + \frac{ac}{u}}.$$

The value livestock production function is a simply quadratic, specified as follows:

$R_i = Px * x_i \left(\alpha - \beta\left(x_i\right)\right)$, where $Px$ is the price of livestock outputs, $\alpha$ , $\beta$ are productivity parameters. When members share a common pasture, we simply use the following livestock production function:

$$R_i = Px * x_i \left(\alpha - \beta\left(x_i + x_j\right)\right)$$

Having defined the functional forms, the following equation is then maximized:

$$\underset{cm_{k-i}, x_i}{Max\pi_i} = k_{OD} * \left[T_i + \left(1 - T_i\right) * \left[P_H\left(CM\right) + k\left(1 - P_H\left(CM\right)\right)\right]\right] * R_i\left(x_i\right) - \overline{c}_{cm} cm - \overline{c}_x x_i$$

Or, for the social optimum, the social optimum

$$\underset{cm_{k-i}, x_i}{Max\pi_i} = \sum_i \left[T_i + \left(1 - T_i\right) * \left[P_H\left(CM\right) + k\left(1 - P_H\left(CM\right)\right)\right]\right] * R_i\left(x_i\right) - \overline{c}_{cm} cm - \overline{c}_x x_i$$

For the scenarios depicted in the paper, we used the model of traps/targets, and assumed that the only impact occurred through tsetse mortality (no additional effect on fly densities). We also fixed the number of animals, so that the only choice variable was traps/targets. Parameters used to generate Scenarios 1 –3 are as follows:

EPIDEMIOLOGICAL PARAMETERS:

$T = 20$

$c = .025$

$a = .25$

$b = .46$

$m = 12.76$

$rinv = 30$

IMPACT OF CONTROL METHOD ON TSETSE MORTALITY PARAMETERS:

$\overline{u}_0 = .02$

$\gamma_{cm} = .51$

$\delta_{cm} = .00425$

$\lambda_{cm}, \varpi_{cm} = 0$

ECONOMIC PARAMETERS:

$R_i = 8000$

$k_{OD} = .9$

$k_{Tryp} = .75$

$\overline{c}_{tt} = 5,10,20$

For Scenarios 4-8, the epidemiological parameters are the same. Remaining parameters are as follows:

IMPACT OF CONTROL METHOD ON TSETSE MORTALITY PARAMETERS:

$\overline{u}_0 = .02$

$\gamma_{cm} = .7$

$\delta_{cm} = .0015$

$\lambda_{cm}, \varpi_{cm} = 0$

ECONOMIC PARAMETERS:

$R_i = 8000$

$k_{OD} = .9$

$k_{Tryp} = .75$

$\overline{c}_{tt} = 10, 11, 12, 15, 25$

# APPENDIX 4--PROOF THAT $cm_{tt-i}^{SO} > cm_{tt-i}^{NC}$, BUT $x_i^{SO} <=> x_i^{NC}$, WHEN BOTH THE CONTROL METHOD AND LIVESTOCK PRODUCTION ARE SUBJECT TO EXTERNALITIES

Recalling the maximization problem from the text in section 4, which considered traps and targets, and so dropped the notation for treated animals since no animals are treated -- the individuals' maximization problem is written as follows:

$$\max \pi_i = k_{OD}\left(P_H\left(CM_{tt}\right) + k_{Tryp}\left(1 - P_H\left(CM_{tt}\right)\right)\right) * P_l x_i f\left(x_i, X_j\right) - \overline{c}_{CM} cm_{tt-i} - \overline{c}_x x_i$$

$$s.t. P_H(CM) \le 1$$

where $X_j = \sum_{j \ne i}^{N} x_j$

Similar to Appendix 1, we simplify notation by setting livestock output price equal to 1, and letting:

$$\left[H + k_{Tryp} S\right] = k_{OD}\left[T_i + \left(1 - T_i\right) * \left[P_H\left(CM_{tt}\right) + k_{Tryp}\left(1 - P_H\left(CM_{tt}\right)\right)\right]\right],$$

$$\frac{\partial P_h}{\partial u}\frac{\partial u}{\partial CM_{tt}} = MP_{CM} \quad \text{and} \quad \frac{\partial R_i}{\partial x_i} = MP_{x_i}$$

First-order conditions are as follows:

$$\frac{\partial \pi_i}{\partial CM_{tt}} = \left(1 - k_{tryp}\right) MP_{CM} * TP_i - \overline{c}_{CM} = 0 \qquad [A30]$$

$$\frac{\partial \pi_i}{\partial x_i} = \left[H + kS\right]\left(f + x_i \frac{\partial f}{\partial x}\right) - \overline{c}_x = 0 \quad [A31]$$

$\forall i$

The SO problem may be re-written as:

$$\max \sum \pi_i = \sum k_{OD}\left(P_H\left(CM_{tt}\right) + k_{Tryp}\left(1 - P_H\left(CM_{tt}\right)\right)\right) * x_i f\left(x_i, X_j\right) - \sum \overline{c}_{CM} cm_{tt-i} - \sum \overline{c}_x x_i$$
$$s.t. P_H(CM_{tt}) \leq 1$$

$$\frac{\partial \pi_i}{\partial cm_{tt-i}} = \sum_i (1-k) MP_{CM}\left(x_i f\left(x_i, X_j\right)\right) - \overline{c}_{CM} = 0 \qquad [A32]$$

$$\frac{\partial \pi_i}{\partial x_i} = [H + kS]\left(f + x_i \frac{\partial f}{\partial x_i} + \sum_{j \neq i} x_j \frac{\partial f}{\partial x_i}\right) - \overline{c}_x = 0 \qquad [A33]$$

$$\forall i$$

Let [A30]=$FOC_{cm}^{NC}$, [A31]=$FOC_x^{NC}$, [A32]=$FOC_{cm}^{SO}$, [A33]=$FOC_x^{SO}$. Below we establish that $cm^{SO} > cm^{NC}$ as in the simpler case where there is no negative externality in livestock production, but that $x_i^{SO} <=> x_i^{NC}$, whereas before, $x_i^{SO} > x_i^{NC}$

First consider the case where $cm^{SO} = cm^{NC}$, meaning that $[H + kS]^{SO} = [H + kS]^{NC}$. Here $FOC_x^{NC} > FOC_x^{SO}$ at the same $x_i$, so $x_i^{NC} > x_i^{SO}$. Given the standard properties of the grazing production function characterized by negative externalities in use, this means that $x_i^{NC} f\left(x_i^{NC}, \sum_{j \neq i} x_j^{NC}\right) < x_i^{SO} f\left(x_i^{SO}, \sum_{j \neq i} x_j^{SO}\right)$. In that case, $FOC_{cm}^{NC} < FOC_{cm}^{SO}$, both because $x_i^{NC} f\left(x_i^{NC}, \sum_{j \neq i} x_j^{NC}\right) < x_i^{SO} f\left(x_i^{SO}, \sum_{j \neq i} x_j^{SO}\right)$ and $MP_{cm}^{NC} < MP_{cm}^{SO}$ evaluated at the same $cm^{SO} = cm^{NC}$. Similarly $cm^{SO}$ cannot be less than $cm^{NC}$, since in this case, $[H + kS]^{SO} < [H + kS]^{NC}$ and $FOC_x^{NC} > FOC_x^{SO}$ -- even more so than before. Again, this means that $x_i^{NC} > x_i^{SO}$ and $x_i^{NC} f\left(x_i^{NC}, \sum_{j \neq i} x_j^{NC}\right) < x_i^{SO} f\left(x_i^{SO}, \sum_{j \neq i} x_j^{SO}\right)$. Since $cm^{SO} < cm^{NC}$, $\frac{\partial MP_u}{\partial cm_i} < \sum \frac{\partial MP_u}{\partial cm_i}$, again more strongly than before; clearly this cannot hold for $cm^{SO} < cm^{NC}$. For $cm^{SO} > cm^{NC}$, $\left[H + kS\right]^{SO} > \left[H + kS\right]^{NC}$, and there is some $x_i^{NC}, x_i^{SO}$ pair that equates $FOC_x^{NC}$ and $FOC_x^{SO}$ but it is possible for $x_i^{NC} <=> x_i^{SO}$. With $x_i^{NC} > x_i^{SO}$ and thus $x_i^{NC} f\left(x_i^{NC}, \sum_{j \neq i} x_j^{NC}\right) < x_i^{SO} f\left(x_i^{SO}, \sum_{j \neq i} x_j^{SO}\right)$, this requires $\frac{\partial MP_u}{\partial cm_i} > \sum \frac{\partial MP_u}{\partial cm_i}$ , which implies that $cm^{SO}$ must be greater than $cm^{NC}$. With $x_i^{NC} = x_i^{SO}$ and thus $x_i^{NC} f\left(x_i^{NC}, \sum_{j \neq i} x_j^{NC}\right) = x_i^{SO} f\left(x_i^{SO}, \sum_{j \neq i} x_j^{SO}\right)$, $\frac{\partial MP_u}{\partial cm_i} = \sum \frac{\partial MP_u}{\partial cm_i}$ which still requires $cm^{SO}$ to be greater than $cm^{NC}$. Finally, it is also possible for $cm^{SO} > cm^{NC}$ and $x_i^{SO} > x_i^{NC}$, since even though $\left(f + x_i \frac{\partial f}{\partial x_i} + \sum_{j \neq i} x_j \frac{\partial f}{\partial x_i}\right) < \left(f + x_i \frac{\partial f}{\partial x_i}\right)$, $\left[H + kS\right]^{SO} > \left[H + kS\right]^{NC}$ so that it is at least possible for $x_i^{SO} > x_i^{NC}$.

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