Ecosocial consequences and policy implications of disease management in East African agropastoral systems

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International research and development efforts in Africa have brought ecological and social change, but analyzing the consequences of this change and developing policy to manage it for sustainable development has been difficult. This has been largely due to a lack of conceptual and analytical models to access the interacting dynamics of the different components of ecosocial systems. Here, we examine the ecological and social changes resulting from an ongoing suppression of trypanosomiasis disease in cattle in an agropastoral community in southwest Ethiopia to illustrate how such problems may be addressed. The analysis combines physiologically based demographic models of pasture, cattle, and pastoralists and a bioeconomic model that includes the demographic models as dynamic constraints in the economic objective function that maximizes the utility of individual consumption under different level of disease risk in cattle. Field data and model analysis show that suppression of trypanosomiasis leads to increased cattle and human populations and to increased agricultural development. However, in the absence of sound management, these changes will lead to a decline in pasture quality and increase the risk from tick-borne diseases in cattle and malaria in humans that would threaten system sustainability and resilience. The analysis of these conflicting outcomes of trypanosomiasis suppression is used to illustrate the need for and utility of conceptual bioeconomic models to serve as a basis for developing policy for sustainable agropastoral resource management in sub-Saharan Africa.

bioeconomics | meta-tools | physiologically based models | cattle trypanosomiasis | tick-borne diseases | malaria

For >50 y, international donors have funded research and development (R&D) on many pressing issues of human and ecosystem health in sub-Saharan Africa. One of these research areas has been trypanosomiasis in cattle (and humans) that restricts husbandry across large part of sub-Saharan Africa (1). The causal agents of trypanosomiasis are species of parasitic protozoan of the genus *Trypanosoma* vectored principally by adults of several species of tsetse flies (*Glossina* spp.). Most programs against trypanosomiasis have been motivated by eradication and control objectives and have had only weak links to the environmental and social science research (1) required to formulate sustainable development policy (2). Here, we examine some of the ecosocial consequences of the suppression of trypanosomiasis on sustainability of an agropastoral community in southwest Ethiopia.

Goodland's (3) clarion call for ecological, economic, and social sustainability recognized that sustainability can be achieved only by keeping the scale of the human economic system within the biophysical limits of the ecosystem. Furthermore, we have learned that the self-repairing capacity of ecosystems cannot be taken for granted because ecosocial change may exceed system resilience (4, 5), which C. S. Holling (6) defined as the magnitude of disturbance a system can experience before it shifts to a different stability domain with different controls on system structure and function. In application, this implies the need to sustain desirable pathways and ecosystem states and to avoid undesirable system configurations (7) in the face of continuous change (8, 9) that can have unexpected and unwanted consequences (10). Most studies on ecosocial resilience in managed systems have been theoretical and/or lacked conceptual and analytical models to access the interacting dynamics of the ecological, economic, and social components of ecosocial systems (11).

We propose 2 general modeling approaches to resolve some of these issues: Weather-driven physiologically based ecosystem models of energy/mass flow in trophic chains and webs including the economic consumer (12–14) and bioeconomic models that includes dynamics of the renewable resource to be managed and the resource manager, i.e., as dynamic constraints in the objective function (15, 16) that maximizes the utility of consumption by individuals under different levels of risk (17, 18). In economics, consumption is the hedonistic use of revenues in ways that do not contribute to firm growth, whereas in nature, consumption is the use of energy in a manner that, on average, does not contribute to growth (e.g., excess reproductive capacity in *r*-selected species and parental care in *K*-selected species) (18) but does contribute to adaptedness. A full suite of economic analogies for resource acquisition and allocation at all levels of natural and human economies, including the conflicting notions of biological and economic demand, consumption, and risk, has been proposed (17–19).

An East African Grassland System

The flow of energy in an East African grassland/wild herbivore/predator system including the biological analog of consumption in each trophic level is illustrated in Fig. 1*A*. These grasslands have largely been converted to agropastoral systems with cattle becoming the dominant herbivore and pastoralists assuming the top position in the food chain with animal trypanosomiasis (tryp) being a major constraint in many areas (Fig. 1*B*) (20). An example of such an agropastoral system is the Gurage ethnic agropastoral community at Luke in the sparsely fertile and semimountain region of southwest Ethiopia (21, 22). In 1995, the Luke villagers initiated a program to reduce the prevalence of trypanosomiasis by treating infected cattle with trypanocidal drugs and by suppressing populations of the tsetse fly vector using odor baited traps. Ecosocial data on the project were also collected and analyzed (22, 23). Tick-borne diseases (tbd) in cattle and malaria in human, among others, are of concern in this area as are the changing patterns of land allocation to agriculture, declining soil fertility, the vagaries of environmental variables (Fig. 2).

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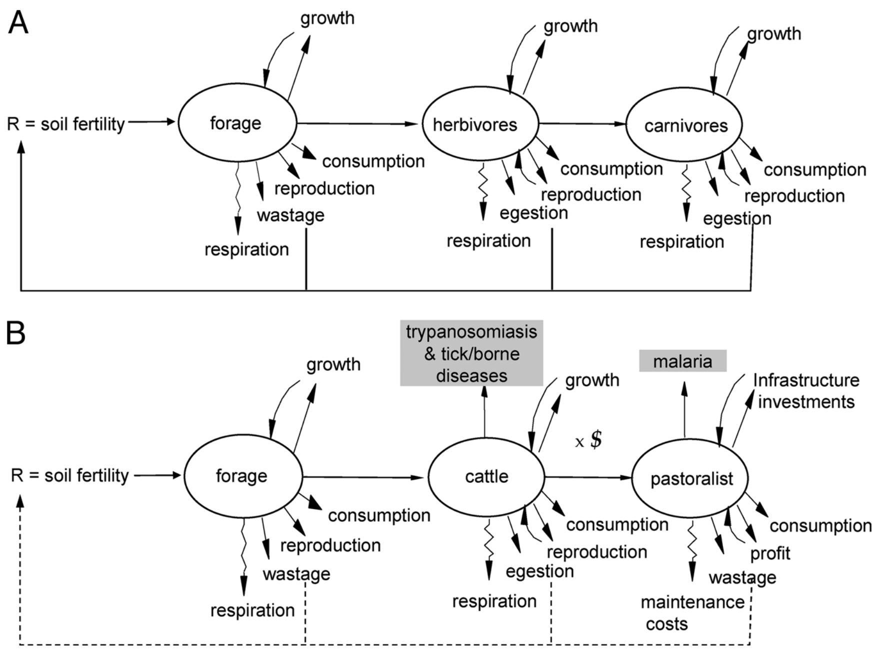

Fig. 1. Two East African grasslands systems. (*A*) A natural system. (*B*) An agropastoral system with disease constraints. The dashed line in *B* indicates that only part of the waste is recycled back to the soil, and the symbol $ indicates the conversion of the mass/energy flow into monetary units (see ref. 20).

Ecological and bioeconomic models are used to analyze the effects of multiple disease constraints on this system. To simplify the analysis, the system as in other previous studies on ecosocial system resilience is assumed closed and of fixed scale (11). The models are first described and then applied to the agropastoral system.

Physiologically Based Demographic Ecosystem Models (EMs)

Mass (energy) flow in a consumer-resource population dynamics model (Eq. **1**) describes the dynamic inflows and outflows in any trophic levels (Fig. 1) by using the same functions across trophic levels including the economic one (12, 13). Multiplication by a constant converts mass to number of individuals or monetary units in human economies (Fig. 1*B*).

Using the notation from ref. 17, let M_i ($i = 1, 2, \ldots, n$) denote the mass of the ith trophic level in a food chain with the dynamics of any trophic level governed by the following equation of motion:

$$\frac{dM_i(t)}{dt} \equiv \dot{M}_i = \theta_i M_i D_i h(u_i) - v_i(D_i) M_i - M_{i+1} D_{i+1} h(u_{i+1}). \quad \textbf{[1]}$$

The components of the model are as follows: D_i is the maximum per-unit biomass demand of the ith trophic level for resource trophic level $i - 1$, and may be viewed as the sum of the maximum outflows for each species including consumption (C); $h(u_i) = (1 - \exp(\frac{-\alpha_i M_{i-1}}{D_i M_i}))$ is the proportions of the per unit demand D_i satisfied by search with $D_i h(u_i)$ being resource acquisition per unit biomass by trophic level i from level $i - 1$ (i.e. the supply), and $0 \le h(u_i) < 1$ equals the supply–demand ratio; α_i is the proportion of level $i - 1$ accessible to the ith level, and $1 - \alpha_i$ is the size of the refuge of the resource; θ_i is the conversion rate of resource and includes wastage; $v_i(D_i) = v_i D_i$ is the cost rate per unit of consumer as a function of the demand rate. In a time varying environment, v for poikilotherms increases with temperature (i.e. the Q_{10} rule), and has special importance in the context of studies on the effects of climate warming (16).

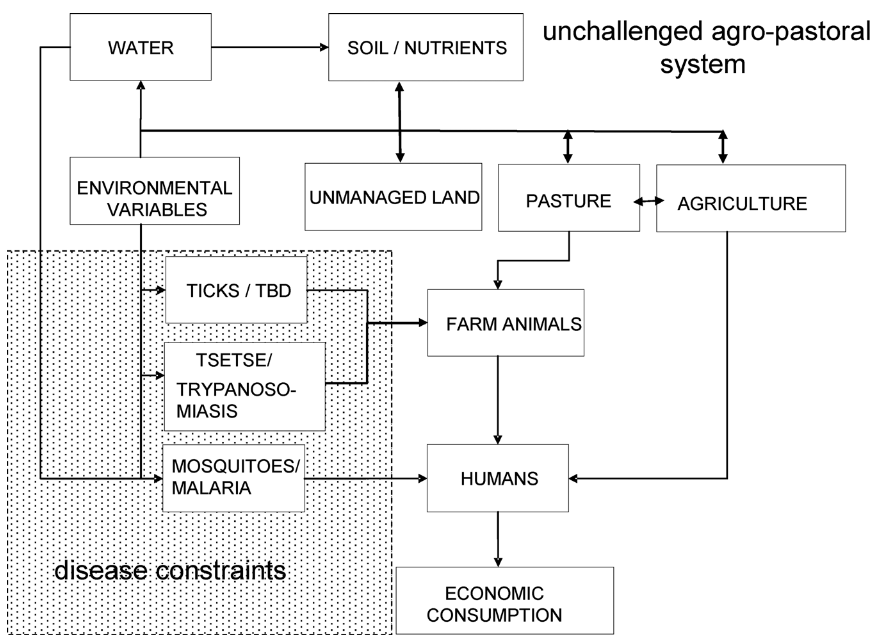

Fig. 2. A holistic view of a hypothesized closed East African agropastoral systems showing disease constraints (shaded area), land allocation, and weather and edaphic variables.

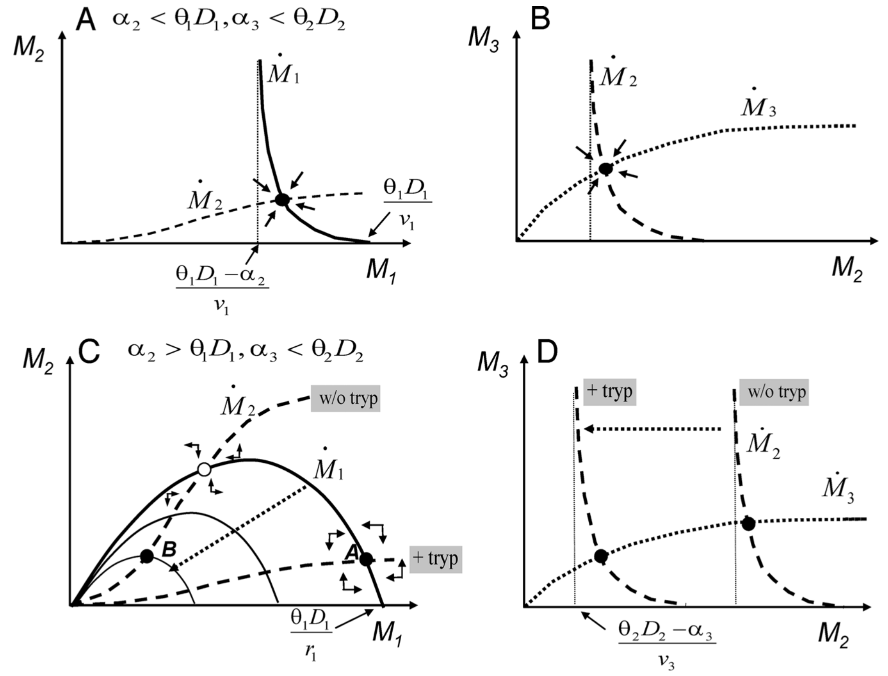

Fig. 3. Isoclines for an East African grassland (M_1), herbivore (M_2), and predator (M_3) system. (*A*) The grassland, herbivore phase plane. (*B*) The herbivore, predator phase plane, and a pasture/cattle/pastoralist system under trypanosomiasis (tryp) pressure. (*C*) The pasture, cattle phase plane with (+tryp) and without (w/o tryp) trypanosomiasis. (*D*) The cattle, pastoralist phase plane. • indicates stable equilibrium, and ∘ indicates an unstable one, and the dotted arrow in *C* indicates a decline in soil fertility.

The function $D_i h(u_i)$ is a ratio-dependent concave per-unit functional response model that includes interspecific competition in the exponent and the possibility of utilizing several resource species each having different αs and consumer preferences. The term $D_i M_i$ is the maximum population demand, and $D_i M_i h(u_i) \leq \alpha_i M_{i-1}$ is the rate of resource depletion by the *i*th level, where $\alpha_i \leq 1$ sets the limits on the extraction by level *i* from resource level $i - 1$. If α_i is sufficiently small compared with the assimilation efficiency of the lower level [$\alpha_i \leq \theta_{i-1} D_{i-1} - v_{i-1}(D_{i-1})$], then the lower tropic level will survive any population size and demand rate of its consumer. The model (Eq. **1**) has been used to study resource allocation dynamics at the individual, population, metapopulation and regional levels (14).

The model is used to describe the dynamics of the East African pastoral system where M_1 is pasture biomass, M_2 is cattle biomass, and M_3 is the pastoralists (Eq. **2**)

$$\dot{M}_1 = \theta_1 M_1 D_1 h(u_1) - v_1(D_1) M_1 - M_2 D_2 h(u_2) S_{\text{tyrp}} S_{\text{tbd}}$$
$$\dot{M}_2 = \theta_2 M_2 D_2 h(u_2) S_{\text{tyrp}} S_{\text{tbd}} - v_2(D_2) M_2 - M_3 D_3 h(u_3) S_{\text{malaria}}$$
$$\dot{M}_3 = \theta_3 M_3 D_3 h(u_3) S_{\text{malaria}} - v_3(D_3) M_3 \qquad \textbf{[2]}$$

Survivorship terms for trypanosomiasis (S_{tryp}) and tick-borne diseases (S_{tbd}) in cattle and malaria in pastoralists (S_{malaria}) are included as constants indicating the level of disease pressure (i.e., 0–1) due to the combined effects of morbidity and mortality. For specific field application, the density-dependent effects of each disease can be estimated from field data as *k* value functions (24), and the other parameters of the model can be estimated from field and/or laboratory data. This enables the model to be used to analyze changes in various agropastoral regions by using weather and the dynamics of soil nutrients and water as forcing variables (12–14). Below, we analyze the general stability properties of natural and managed East African grasslands to assess the ecological consequences of human interventions.

Analysis of a Natural Grassland/Wild Herbivore/Predator System

Wildlife is tolerant of trypanosomiasis ($S_{\text{tryp}} \approx 1$) but may carry high levels of infection (20) (Fig. 1*A*). The shapes of the zero isoclines and the equilibrium properties of Eq. **2** depend on the value of the apparency rate (α_{i+1}) of the renewable resource to the consumer relative to the maximum per-capita growth rate of the resource ($\theta_i D_i$) (13). The inequalities for the natural grassland system are $\alpha_2 < \theta_1 D_1$ and $\alpha_3 < \theta_2 D_2$ yielding the zero isoclines for levels M_1 and M_2 depicted in Fig. 3*A*. The direction of the inequality $\alpha_2 < \theta_1 D_1$ is due to the high per-unit biomass growth rate of grass relative to the ability of wild herbivores to consume it. Similarly, the biomass growth rate of herbivorous wildlife is high relative to the predation pressure (i.e., $\alpha_3 < \theta_2 D_2$) yielding the zero isoclines in the (M_2, M_3) phase plane (Fig. 3*B*). The resource species have a maximum population at $(\theta_i D_i)/v_i$ and cannot be driven below the vertical asymptotes at $(\theta_i D_i - \alpha_{i+1})/v_i$. Stable equilibrium (•) occur in both the (M_1, M_2) and (M_2, M_3) phase planes.

Analysis of a Managed Grassland/Cattle/Agropastoralist System

In contrast to natural systems, trypanosomiasis pressure in agropastoral systems (+tryp) is high, and cattle are susceptible resulting in a low value for $S_{\text{tryp}} \to 0$. When healthy, cattle have an efficient search behavior and a larger per-capita demand rate than wild herbivores (i.e. $\alpha_2 > \theta_1 D_1$), and hence the shape of the isoclines for the pasture (M_1) is humped (Fig. 3*C*) (15) as proposed by Noy-Meir (25). Pastoralists view herd size as a measure of wealth, and as insurance during periods of drought or high incidence of disease, and hence prefer not to consume or sell them (26). For this reason, the shape of the M_2 isoclines (Fig. 3*C*) is sigmoid as in Fig. 3*A* (e.g., $\alpha_3 < \theta_2 D_2$).

Under high trypanosomiasis pressure ($S_{\text{tryp}} \to 0$; +tryp), cattle density (M_2) is low ($>(\theta_2 D_2 - \alpha_3)/v_2$) (Fig. 3*D*), and pasture level (M_1) is high, yielding a stable equilibrium at point *A* (•, Fig. 3*C*). However, suppression of tsetse/trypanosomiasis drives $S_{\text{tryp}} \to 1$ and allows cattle populations to increase resulting in an unstable equilibrium (∘) that leads to overgrazing and the depletion of soil nutrients. This causes the M_1 isocline to contract leftward (dotted arrow, Fig. 3*C*) resulting in a new stable equilibrium at low M_1 and M_2 (point B, •, Fig. 3*C*). This is a demonstration of exceeding resilience capacity that takes the system to a new but unfavourable stable point (6).

Viewing the isoclines in the (M_2, M_3) phase plane shows that trypanosomiasis suppression causes a rightward shift in the M_2 isocline that affects the level but not the shape of the M_3 isocline

(Fig. 3*D*). However, overgrazing causes a reversal or leftward shift in the M_2 isocline in the (M_2, M_3) phase plane that could be as extreme as the effects of high trypanosomiasis pressure (Fig. 3*D*) suggesting that solving the trypanosomiasis problem may lead an overgrazing problem. The ecosocial consequences of trypanosomiasis suppression were examined by ref. 26 and are reviewed and expanded below by using the bioeconomic model.

Bioeconomic Model of Managed Grassland/Cattle/Agropastoralist Systems

For clarity, Eq. **2** is simplified to represent the dynamics of M_2 and M_3 given a constant amount of forage M_1 (Eqs. **3** and **4**) (see ref. 17):

$$\frac{dM_2}{dt} \equiv \dot{M}_2 = G(M_1, M_2) - v_2(D_2)M_2 - F(M_2, M_3) \qquad [3]$$

$$\frac{dM_3}{dt} \equiv \dot{M}_3 = \theta \cdot F(M_2, M_3) - v_3(D_3)M_3 \qquad [4]$$

where $G(M_1, M_2) = M_2 D_2 h(u_2)$ is the quantity of M_1 eaten by cattle, $F(M_2, M_3) = M_3 D_3 h(u_3)$ is the flux of M_2 harvested by pastoralists (M_3), and $v_2(D_2)M_2$ and $v_3(D_3)M_3$ are the respiration rates. The functions $G(\cdot)$ and $F(\cdot)$ satisfies the necessary concavity and positive marginal productivity conditions of economic models because both increase with resource levels and decrease with intraspecific competition among consumers [i.e., the exponent $-\alpha_i M_{i-1}/D_i M_i$ in $h(u_i)$, (Eq. **1**)] (13). This biology in reduced form is included in the bioeconomic objective function (Eq. **5**).

Bioeconomic Objective Function

In economics, the objective function for resource exploitation by all individuals of M_3 seeks to maximize the present value utility of individual consumption (C) from the revenue (energy) stream and is expressed as:

$$\max_{C,D} \int_0^{\infty} e^{-\delta_{\text{tryp}} t} M_3 U(C) dt \qquad [5]$$

subject to the dynamics constraints of the managed resource M_2 (Eq. **3**) and the pastoralists M_3 (Eq. **4**), $e^{-\delta_{\text{tryp}} t}$ is the discount factor reflecting the level of risk of trypanosomiasis, t is time, and the per-capita demand (D) and consumption (C) rates are control variables (17). C is included in the model via the monotonically increasing concave utility function of individuals $U(C)$ that has properties $U'(C) > 0$, $U''(C) < 0$ and $U'(C) \to 0$ as $C \to \infty$.

By Pontryagin's maximization principle, the maximization of Eq. **5** by all consumers M_3 subject to population dynamics constraints (Eqs. **3** and **4**) is equivalent to the maximization of the current value Hamiltonian (Eq. **6**) (17, 27):

$$\mathcal{H} = U(C)M_3 + \lambda_1(g - F) + \lambda_2[\theta F - (vD + C)M_3] \qquad [6]$$

where λ_1 and λ_2 are costate or auxiliary variables associated with the dynamic constraints. In particular, λ_1 is the Lagrange multiplier that represents the marginal utility of income from harvesting M_2. The necessary conditions for an optimal solution of Eq. **6** are satisfied, $C^*(\delta)$ is an increasing function of δ, and because $\dot{\lambda}_1$ and $\dot{M}_2$ do not depend on M_3 and $\lambda_1 \le U'(C^*)(\theta - v)$, this allows the analyses to be restricted to $[0, U'(C^*)(\theta - v)] \times [0, \infty]$ in the (λ_1, M_2) phase space. The extensive mathematical analysis is outlined in ref. 17 and is not reproduced here.

Two solutions arise: The optimal societal solution for resource exploitation by all pastoralists maximizes the present value utility of individuals expending from the revenue stream in ways that do not contribute to growth (consumption) and yet assures the persistence of the renewable resource over an infinite time horizon (i.e., renewable resource sustainability), and the competitive solution results where pastoralists pursue self-interest goals with $\lambda_1 \to 0$ as $\delta \to \infty$ resulting in overexploitation of the resource.

Bioeconomic Effects of Reducing Trypanosomiasis Risk

Ecosocial Data. The trypanosomiasis program at Luke, Ethiopia, was initiated in 1995, and by 2005, tsetse populations were very low, and the prevalence of trypanosomiasis fell from 29% to 10% (23, 26). The prevalence of disease would have been lower had infected cattle not been continually introduced from outside the suppression zone and trypanosomiasis not been endemic in wildlife. Cattle numbers including oxen increased 5-fold, calving rates 8.2-fold, milk production 13-fold, per-capita income doubled, and human populations increased 40%. Increases in highly susceptible oxen allowed cultivated land to increase from 12 ha in 1995 to 506 ha in 2005. Increased revenues enabled the building of a school and allowed the villagers to continue the tsetse/trypanosomiasis suppression program. The latter 2 items are measures of economic consumption as well as indicators of the Luke community's readiness to adopt change and reacted to new opportunities. Studies undertaken in Africa under different cultural and ecological conditions have also shown fast economic responses to tsetse control operations (28).

Predictions of the Bioeconomic Model. The dynamics of the bioeconomic model can be reduced mathematically to the zero isoclines for the shadow prices for cattle (λ_1) and cattle populations (M_2) at different levels of trypanosomiasis risk (δ_{tryp}) (see appendix in ref. 17). As observed, the model predicts that a dramatic reduction in risk ($\delta_{\text{tryp}} \to 0$) and increased productivity (θ_2) lead to increased cattle (M_2) and human (M_3) populations, and to increases in the marginal value (λ_1) of cattle. Some of the dynamics are summarized in the $(\lambda_1, M_2, \theta_2)$ phase space (Fig. 4) where positive changes in λ_1, M_2 and θ_2 along the optimal path (point *A* to *B*) are measures of increasing economic health. All of the points along the optimal path are saddle points. In contrast, $M_{2,c}$ on the abscissa and points along the trace from it $(\lambda_1 = 0, M_2, \theta_2)$ is the path of the competitive solution. Point $M_{2,e}$ on the abscissa is a hypothetical level where the system collapses (17, 18).

As δ_{tryp} decreases from an initial high level (Fig. 4, point *A*), the optimal trajectory (λ_1^*, M_2^*) increases on θ_2 to the point of maximal societal benefit (point *B*). However, overgrazing beyond *B* reduces natural capital (M_1 and soil fertility) resulting in a reversal of θ_2 with the optimal path of λ_1^*, M_2^* (the dashed line) declining in the direction of system collapse (i.e., $M_{2,e}$; point *C*). The rate of change of the optimal trajectory from *A* to *C* may be relatively fast, whereas the reversal or remediation from *C* back to the "maximum optimal societal benefit" at *B* is slow commensurate with the time required to rebuild soil structure and function. This illustrates the effects of fast and slow variables in the system (5, 7).

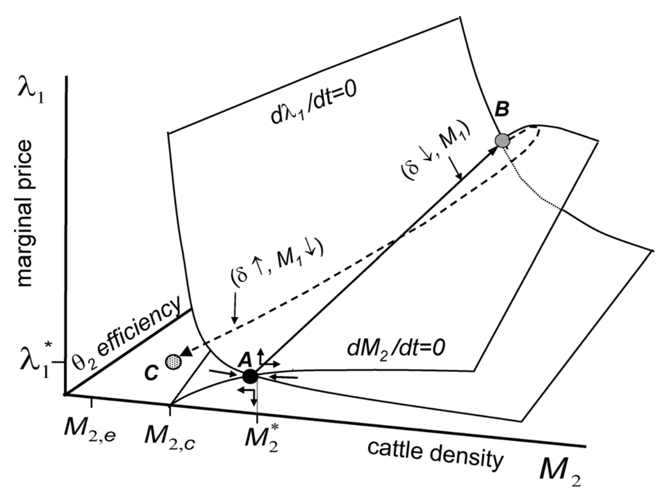

Fig. 4. The (λ_1, M_2) phase plane on increasing θ_2 for an East African agropastoral system (see text).

If the Luke villagers choose the competitive solution as suggested by their cultural view of herd size as insurance and wealth (29), the path to over exploitation will occur much sooner along the trace from $M_{2,c}$ (Fig. 4).

Adding Other Disease Constraints

It is difficult to introduce the contribution of other sources of risk into the bioeconomic model and to separate their contribution to total risk ($\delta_{total} = \delta_{tryp} + \delta_{tbd} + \delta_{malaria} + \cdots$) (18).

It is, however, quite straightforward to analyze the separate effects by using the zero isoclines of the agropastoral system model (Eq. **2**), wherein the disease effects are introduced as increased morbidity and mortality of affected hosts.

With reduced trypanosomiasis (w/o tryp) and the associated increases in cattle (M_2), ticks and tick-borne diseases (+tbd) are expected to increase causing a reversal in cattle density (Fig. 5*A*). This suggests that gains from suppression of trypanosomiasis could be lost as the independent effects of tbd are unleashed (Fig. 5*C*). In addition, the cost of acaricides to control ticks (i.e., a component of v_3 in Eq. **2**) would cause the M_3 isocline to shift downward (Fig. 5*B*). As with trypanosomiasis, decreases in cattle population resulting from tbd would enhance pasture recovery (dotted line in Fig. 5*A*).

With human populations increase, the incidence of malaria is expected to increase in the absence of investments in control. The effects of malaria enter the model (Eq. **2**) as an increase in morbidity and mortality to pastoralists that lower the M_3 isocline (Fig. 5*B*). The model predicts an unlikely increase in cattle densities (M_2, Fig. 5*C*) only because the negative feedback of malaria to cattle herding and care is not included in the model. Last, the increase in land use for agriculture will come at the expense of grazing land (M_1) reducing the system's carrying capacity for cattle.

Thus, the consequences of reducing risk from trypanosomiasis will increase risk from other diseases in cattle and humans (Fig. 5*C*) that may cancel many of the gains of the tsetse/trypanosomiasis suppression program. On the bleak positive side, heavy disease pressure will cause a reversal, albeit slow, in the decline of pasture quality.

Discussion

Argument concerning agropastoral systems sustainability in East Africa continues to imply some unspecified level the system should be maintained and from a management perspective to the need for societal solutions to preserve system resilience (4, 7). Holling's (6) concept of resilience speaks to the amount of change a system can tolerate before it collapses to another state, while Ludwig et al. (30) have cautioned to distrust claims of sustainability because human response and motivation are part of the system to be managed, and shortsightedness and greed make this difficult.

Commonly, partial tools of analysis such socioeconomic surveys and expert opinions have been used, but these methods failed to link important components of ecological–economic–social systems in a dynamic framework (31). Researchers and policy makers in international R&D programs must be able to capture the essence of resource management issues in a manner that can help anticipate unexpected consequences of development. Our bioeconomic analysis of the eco-social changes resulting from the successful suppression of animal trypanosomiasis by agropastoralists at Luke, Ethiopia, circumvents many of these limitations and yields 2 solutions for agropastoral system management: The optimal societal solution that maximized the present value of individual utility of consumption and yet assures the persistence of the renewable resource over an infinite time horizon (i.e., renewable resource sustainability), and the competitive solution, wherein individuals pursue self-interest goals that consistently lead to the destruction of the resource base as a consequence (17, 18). We found that adoption of the societal solution may still lead to overexploitation of resources because overexploitation "smaller is often not detectable until it is severe and often irreversible" (30), and to avoid this, preemptive action may be required "before the growing scarcity of natural capital makes its importance painfully obvious and the costs of restoration painfully high" (32).

The ecosocial changes resulting from the successful suppression of animal trypanosomiasis yielded conflicting outcomes. On the positive side, the data show increases in cattle and human populations and an increased diversion of land to agriculture (23, 26), whereas on the negative side, large increases in cattle density will increase overgrazing and the risk from diseases (e.g., tick-borne diseases), and further increases in human populations may lead to overpopulation, diversion of more of the limited land to agriculture, increased demand for resources, and increased risk from malaria and other diseases. These negative effects could more than wipe out the gains from suppression of trypanosomiasis. If, as we suspect, the Luke community has adopted the competitive solution, the negative ecosocial consequences may arise rapidly,

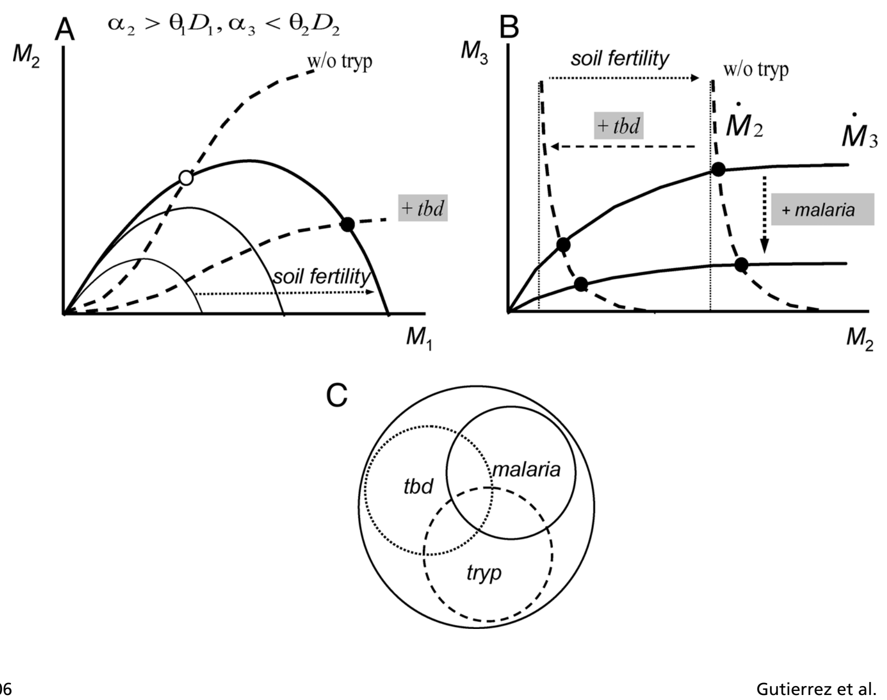

Fig. 5. The phase plane for combinations of M_1, M_2 and M_3 with (M_1, M_2) phase plane without tsetse/trypanosomiasis (tryp) and adding the effects of tick-borne diseases (tbd) (*A*), (M_2, M_3) phase plane adding malaria (*B*), and a Venn diagram of some competing disease risks in the systems (*C*).

be dire, and more difficult to correct. Unchecked, the compounding effects of these changes could lead to the collapse of the agropastoral economy with ecosocial reorganization in an eroded environment the remaining option as the pastoral life disappears (33). Thus, although trypanosomiasis suppression is inexpensive and can have rapid positive impact on agropastoral communities, conflicting outcomes will arise that will require self-governance structures to avoid negative consequences and to manage ecosocial change for system sustainability. Among the needed changes are grazing rules to preserve pasture productivity and curbs on human population growth and associated increasing demands for resources. Empirical design principles derived from long-enduring institutions governing sustainable resource management in different parts of the world (34) have been identified and could help point the way forward for East African agropastoralism.

Furthermore, opening an ecosocial system such as Luke to a market economy will introduces additional interactions and interdependencies between Luke and surrounding communities and regional and national institutions. Climate change is also expected to impact the system and further complicate sustainable management issues, and although these effects can be introduced in the model (14), the major problem remains of how to implement the understanding gained for the benefit of resource and human-population management.

Overexploitation of renewable resources is a recurring problem, and the human record in solving them is not encouraging. What is clear is that no amount of analysis can circumvent the maxim that local solutions will require local adaptation in culture and institutions to cope with the evolving challenges to ecological, social, and economic resilience in whatever form they may take (7, 30). Local human ingenuity and adaptability must be encouraged to flourish to address these challenges (29), and local peoples and their knowledge of the system must become active partners in the solution of local resource management problems as proposed by P. E. Kenmore for rice production in Southeast Asia (35) and more generally by Ludwig (36).

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