Ecosystems

Burden or Bounty?

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The World Bank
Africa Region
Sustainable Development Department
May 2014
Abstract

This paper presents a somewhat novel approach to explore the economic contribution of ecosystems. It develops linked models to capture connections between resource stocks and flows and the resulting microeconomic and macroeconomic impacts. A bioeconomic model is developed that is imbedded into a computable general equilibrium (CGE) model. Incorporating imperfect regulation, the bioeconomic model characterizes optimal policies, while the CGE model explores the economy-wide consequences of possible changes to the ecosystem. The model is parameterized and calibrated to the case of the Serengeti ecosystem which is perhaps the most intensively researched biome with a relative abundance of data. This ecosystem is also undergoing rapid change from a host of factors related to developments within and around the protected area system. The analysis identifies the contribution of the ecosystem to the economy and finds that changes in tourism and bushmeat hunting have surprisingly diffuse economy-wide impacts, that are especially large in the rural sector. To guard against overstatement, ecosystem impacts are under-stated relative to other effects. The results suggest that linkages to the natural resource sector (backward and forward multipliers) are important and neglecting these may lead to biased estimates.

This paper is a product of the Sustainable Development Department, Africa Region. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at rdamania@worldbank.org.
Ecosystems - Burden or Bounty?

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Key Words: Renewable resources, bioeconomic modeling, tourism

JEL Codes: Q57; Q59; Q20; Q29

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\textsuperscript{2} The authors are grateful to Michael Toman, Luc Christiaensen, Jacques Morisset and Anders Skonholt for comments on earlier drafts of this paper.
1. Introduction

Nestled within east Africa’s Great Rift Valley lies the Serengeti plain which spans more than 25,000 km². In the language of the Maasai, “Serengeti” is the term for a “great open space”. It is home to an extraordinary diversity and density of wildlife, with over a million wildebeest, large herds of zebra, gazelles, elephants and rhinos that are accompanied by numerous other ecologically significant species (Sinclair 1995; Sinclair et al. 2008). The annual wildebeest migration is the largest movement of animals in the world and has become a tourist spectacle. The migration plays a crucial biological role that enables large herds of ungulates to track shifts in forage as they journey from the parched grasslands of Tanzania, to more fertile pastures in Kenya. In any given year tourism typically generates the bulk of foreign exchange for Tanzania, often surpassing mineral export revenues. Understanding the economic role and linkages of this ecosystem with sectors of the economy is arguably not without significance for an economy so dependent upon its revenues.

This paper presents a somewhat novel approach to explore the economic contribution of ecosystems. It develops linked models to capture connections between renewable resource (wildlife) stocks and flows and the resulting micro and macroeconomic impacts. The approach is then applied to the Serengeti ecosystem which is one of the iconic tourist destinations in Africa. Methodologically this paper builds upon the familiar bioeconomic models that have been used in the African context (see e.g., Skonhoft and Solstad (1996, 1998), Skonhoft (1998), Bulte (2003), Fischer et al. (2011)). It extends the approach by incorporating imperfect regulation together with an analysis of multiple and conflicting uses of renewable resources through tourism, trophy hunting and bushmeat hunting and competition for land for agriculture. To our knowledge there have been no earlier attempts to formalize this problem of resource rivalry. The results suggest that observed responses to pressures often depart from optimal policies. For instance when carrying capacity declines, optimality calls for an increase in land allocated to wildlife – the reverse of what is typically observed. Likewise the optimal response to increasing agricultural profits entails intensification of agriculture, with more land devoted to wildlife – the opposite of current observable trends especially in Africa. The paper
links this framework to a CGE model that incorporates a renewable resource (wildlife) sector and includes tourism, bushmeat and trophy hunting of natural resource (wildlife) stocks. A CGE approach seems appropriate in contexts where the size of the tourism and wildlife sectors are sufficiently large. Simulations using available parameters for the Serengeti provide an indication of impacts and resource resilience. The exercise suggests that each change when considered in isolation is less significant than the combined impacts which have synergistic effects. Increased enforcement and more stringent regulations on harvesting or illegal land conversion (to agriculture), do little to correct outcomes once irreversible changes occur. The CGE model tracks the impacts across the economy and the results are often surprising. The simulations indicate that changes in tourist revenues and wildlife harvesting (especially for bushmeat) tend to have diffuse impacts that are transmitted through the economy, with the largest effects occurring among the (poorer) rural households. This reflects the multipliers of the natural resource sector, as well as the effects of the tourism sector through the exchange rate. Policies that stimulate these sectors therefore have broad impacts due to the wide linkages. In short the results suggest that policies that boost (or degrade) the Serengeti could have wide impacts that seem to dominate strategies in alternative sectors due to the exchange rate impacts as well as the multiplier linkages.

This paper is related to a large and growing body of literature in bioeconomics and in particular on the Serengeti. The allure of the Serengeti has inspired a vast amount of research and it is perhaps the most intensively researched ecosystem in Africa, with studies that have tracked wildebeest migration and demography for close to a century. Especially notable are the cross-disciplinary studies that recognize the need to explore the economic drivers of environmental change. In a pioneering early paper Barrett and Arcese (1998) examined the effectiveness of integrated conservation and development (ICDP) approaches and concluded that these may have limited durable impact – a result confirmed by much subsequent research. Johannesen and Skonhoft (2004) explore the role of property rights on poaching incentives and find that contrary to expectations assigning property

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3 The focus is on a reduction in the carrying capacity, and increased pressures for land conversion to alternative uses. There are a number of compelling reasons to suggest that carrying capacity could decline. There is increased grazing pressure from an expanding population of domestic cattle, additionally as noted by Holdo (2011) development could lower carrying capacity by over 30 percent.
rights (ownership) could lead to more hunting when the nuisance effects of crop damage from wildlife dominates. In contrast Holdo et al (2010) develop a spatially explicit simulation model of the Serengeti (termed HUMENTS) to examine the combined pressures of rainfall variability and poaching on wildebeest populations. In an extension Holdo et al (2011) use the model to explore the effects of a barrier to migration on the wildebeest population. The results are striking and suggest a median decline of about 38 percent of the population resulting from a fall in the carrying capacity of land due to a loss of access to higher quality forage. A related strand of literature explores the determinants of, and motivations for, hunting in the Serengeti (see, e.g., Johannsen (2005)). Finally, using an “Almost Ideal Demand System” Rentsch and Damon (2013) examine the consumption elasticities of bushmeat hunting and find a high cross-price elasticity between bushmeat and other sources of protein (especially fish and beef), implying that households would readily reduce consumption of bushmeat if offered modest price incentives (such as subsidies for legal meat, or harsher penalties for illegally sourced bushmeat). None of these papers has combined a bioeconomic economic model with a CGE to examine broader interactions and none of the theoretical models addresses optimal policy responses in a closed form bio-economic model. It hoped that this paper presents policy relevant results in a framework that extends existing analytical approaches.

The remainder of this paper is organized as follows. Section 2 outlines the benchmark bioeconomic model and derives analytical solutions for defining optimum regulatory levels and allocations between competing users. Section 3 introduces imperfect regulation and identifies departures from the benchmark model. This is followed by numerical simulations in the following section. Section 5 briefly describes and presents results for the CGE analysis while Section 6 concludes the paper.

2. The Benchmark Model

This Section begins by presenting a simplified benchmark model to obtain closed form solutions and compare outcomes to those under imperfect regulation. There are three agents in the model that use the ecosystem: tourists who are attracted by the abundance of wildlife, trophy hunting ventures that
are allocated a hunting quota by the government and locals who engage in two types of activities - they
hunt wildlife (bushmeat) for consumption and farm.

In keeping with the existing literature the focus is on a single representative species - the wildebeest.
This simplification is reasonable in the context of the Serengeti where wildebeest fulfill important
ecological functions as ecosystem regulators, with significant impacts on the local economy.
Ecologically wildebeest are regarded as a keystone species, whose numbers regulate biomass growth,
tree dynamics, predator populations and ungulate competitors (Sinclair et al 2008). Reducing their
numbers from habitat patches results in marked changes in biodiversity and community structure
(Terborgh et al 2002). All of this suggests that as a first approximation a focus on the dominant species
is reasonable in a modeling context. Data on tourism indicate that tourist numbers closely correlate
with wildebeest populations suggesting that they remain an important draw card for visitors,
especially because of the migration. For the locals, the wildebeest are an important source of protein
and the migration periodically brings large numbers into proximity of humans and increases their
vulnerability to hunting outside protected areas.

Due to the paucity of quantitative information, in what follows functional forms are used that
economize on data requirements. Tourists are assumed to visit the area to view wildlife and their
numbers $T_r$, depend on the stock of wildlife. For simplicity, wildlife stocks are proxied by wildebeest
population $W$ (Sinclair op cit). The number of tourists is then given by:

$$ T_r = AW^\beta; \quad 0 < \beta < 1 $$(1a)

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4 A regression yields the following log tourist numbers = 0.5 log(wildebeest) + 0.211 time trend, with an $R^2 = 0.879$ though the
correlation need not imply casualty.

5 As noted earlier this species is disproportionately impacted by hunting leading to concerns that this could result in wider trophic
changes with impacts across the food chain (Holdo et al).

6 Note that it is possible to interpret this formulation as the outcome of a utility maximizing problem such that tourist utility
$U(T) = \frac{1}{b} (WT)^b - PT$ where $P$ is price per tourist day, which upon maximization yields $T_r = \left( \frac{W^b}{P} \right)^{\frac{1}{1-b}}$; In equation (1) this
implies that $A = \left( \frac{1}{P} \right)^{\frac{1}{1-b}}$ and $\beta = b/1 - b$, or equivalently $b = \beta/(1+\beta)$. Hence $\frac{dT}{dP} = -\frac{1}{1-b}(W/P)^{(b/(1-b))}$ and finally for completeness
we note that the price elasticity of $T$ is $-P/(1-b)$.5
The other agent in the model are the trophy hunting concessionaires who are granted an allocation $\Omega$ by the government. The harvest of wildebeest allocated to trophy hunting is:

$$T_h = \Omega W$$ (1b)

Locals in the model engage in farming and hunting for bushmeat. Numerous empirical studies confirm that bushmeat remains an important source of protein for the (mainly) poor households that live in the Serengeti ecosystem. In some parts of the ecosystem bushmeat hunting is legal, though subject to controls. Let $N$ be the legal allocation of bushmeat, the model subsumes the case where all hunting is illegal ($N=0$) and allows for poaching and noncompliance in subsequent sections. Farming in this context could represent either livestock rearing (the traditional Maasai activity), or crop production (dominant among other groups). An important feature of the model is that there is competition for land used either for farming or wildlife. Let $L = L_w + L_g$ be the total amount of land allocated to wildlife and agriculture respectively and further assume that $L_w = L_p + L_{wnp}$, where, $L_p$ denotes land in the protected national park, $L_{wnp}$ is land outside the national park used by wildlife. Finally let $L_{np} = L_{wnp} + L_g$ be land outside the protected areas. Utility to locals from hunting and farming is given by:

$$V(\Pi) = [(\rho - c)(WN) + (P - k)((L - L_w))]^\vartheta = [\pi_N WN + \pi_L (L - L_{np} - L_p)]^\vartheta ; \vartheta < 1$$ (1c)

where $\rho$ and $c$ define the benefits and costs respectively from the harvest of wildebeest and $\pi_N = (\rho - c)$ while $\pi_L = (P - k)$ are unit profits from land used in agriculture, $L_g = L - L_w$.

Social welfare is simply the aggregate utility of the three agents and takes a Cobb-Douglas specification, defined as:

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7 Trophy hunting in Tanzania is largely outsourced to commercial organizations who market the hunting experience as an elite and high-end activity often with “guaranteed” kills (Kideghehseso 2006). The aim here is not to examine the bioeconomics of trophy hunting but to explore the interactions of multiple uses, so we abstract from more detailed industrial organization concerns in what follows.

8 In an extension we explicitly model labor supply decisions. This adds realism but does not alter the qualitative conclusions, so is ignored in what follows.

9 Note that $\rho$ and $c$ can be derived from the primitives of a Cobb-Douglas utility function. We avoid this step in order to economize on space.
where $\beta_\alpha + \gamma_\theta + \phi = \varphi < 1$, $\sigma = \beta_\alpha + \gamma_\theta = \varphi - \phi$ and $F = A^\alpha B^\theta$.

The stock of wildebeest evolves according to the usual logistical differential equation. This functional form is not only analytically convenient but has also been parameterized for the Serengeti wildebeest (Stratton 2012):

$$\frac{dW}{dt} = rW(1 - \frac{W}{qL_w}) - \Omega W - NW$$

(2b)

where $r$ is the intrinsic growth rate, $q$ is a parameter that measures the carrying capacity per unit of land available for wildlife and $\Omega$ and $N$ are the harvest of trophy hunters and locals respectively. We begin by deriving optimal allocations in an idealized situation of full compliance, with control variables $\Omega, N, L_w$, subject to the dynamics of $W$ in (5). The Hamiltonian can be defined as:

$$H = FW^\sigma\Omega^\phi[\pi_N WN + \pi_L L_g]^\phi + \mu[rW(1 - \frac{W}{q(L - L_g)}) - \Omega W - NW]$$

(3a)

where $\mu$ is the co-state variable.

The first-order conditions for a maximum are:

$$\frac{\partial H}{\partial \Omega} = \eta \frac{U}{\Omega} - \mu W = 0$$

(3b)

$$\frac{\partial H}{\partial N} = \varphi \frac{U}{\Pi} \pi_N - \mu = 0$$

(3c)

$$\frac{\partial H}{\partial L_g} = \varphi \frac{U}{\Pi} \pi_L - \mu r - \frac{W^2}{q(L - L_g)^2} = 0$$

(3d)

$$\mu - \mu = -\frac{\partial H}{\partial W} = -\sigma \frac{U}{W} - \varphi \frac{U}{\Pi} \pi_N W - \mu r - 2 \mu r - \frac{W}{q(L - L_g)} + \mu \Omega + \mu N$$

(3e)

Using equations (3d) and (3e) and recalling that $L_g \leq L_{wp}$, the optimal allocation of land to wildlife is:
\[ L_w = L - L_g = W \frac{r \pi_N}{q \pi_L}, \quad \text{if} \quad L_g \leq L_{np} \quad \text{and} \quad L_w = L_p \quad \text{otherwise.} \quad (4) \]

Thus the land allocated to wildlife at the optimum is directly proportional to the relative payoffs to hunting, relative to farming \((\pi_N/\pi_L)\) with an adjustment for the carrying capacity of land \((q)\) and the intrinsic growth rate \((r)\). Observe that \(L_w\) is declining in \(q\) since a higher carrying capacity implies that less land needs to be allocated to wildlife to achieve any given payoff.\(^{10}\) Combining equations \((3b) - (3e)\) yields the optimal change in the stock of wildlife:

\[ \frac{\dot{W}}{W} = r(1 - \sqrt{\frac{\pi_L}{qr \pi_N}}) - \Omega - N \quad (5) \]

By equation \((5)\) it is clear that non-negative growth requires that the relative profitability of farming is sufficiently low for an equilibrium to be sustained (i.e. \(\frac{\dot{W}}{W} > 0 \iff \frac{\pi_L}{\pi_N} < \frac{q}{r} (r - (\Omega - N))^2\)).

The optimal growth paths of the control variables are given by:

\[ \frac{\dot{\Omega}}{\Omega} = \frac{1}{\alpha \beta} \left[ r(1 - 2 \sqrt{\frac{\pi_L}{rq \pi_N}}) - \delta \right] + \frac{\Omega}{\eta} \quad \text{and} \]

\[ \frac{\dot{N}}{N} = \frac{1}{\omega_N(\alpha \beta)} \left[ r(1 - 2 \sqrt{\frac{\pi_L}{rq \pi_N}}) - \delta \right] + \frac{[1 - (2 \omega_N - 1) \eta]}{\eta \omega_N} \Omega - \frac{2 \omega_N - 1}{\omega_N} [r(1 - \sqrt{\frac{\pi_L}{rq \pi_N}}) - N] \quad (6a) \]

\[ \quad \text{and} \]

\[ \frac{\dot{N}}{N} = \frac{1}{\omega_N(\alpha \beta)} \left[ r(1 - 2 \sqrt{\frac{\pi_L}{rq \pi_N}}) - \delta \right] + \frac{[1 - (2 \omega_N - 1) \eta]}{\eta \omega_N} \Omega - \frac{2 \omega_N - 1}{\omega_N} [r(1 - \sqrt{\frac{\pi_L}{rq \pi_N}}) - N] \quad (6b) \]

The results under perfect regulation are intuitive. A higher value of tourism \((\alpha \beta)\), or a lower regenerative capacity \((r)\) diminishes growth of both types of hunting, whereas a higher carrying

\(^{10}\) Since agriculture occurs only on non-park land \(L_{np}\) this can be stated as:

\[ L_w = L_p + (L_{np} - L_g) = (L - L_{np}) + W \frac{r \pi_N}{q \pi_L}. \]
capacity \((q)\) unambiguously leads to higher harvest rates in both sectors\(^{11}\). The intuition is straightforward - greater tourism benefits and a lower regenerative capacity of wildlife, favor non-consumptive tourism. While in (6b), the rate of increase in bushmeat hunting rises with the level of trophy hunting (suggesting complementarity) when \(\eta\) is sufficiently small.

Finally for later use we note that solving for the steady state values yields:

\[
\Omega_{ss} = \frac{\eta}{\alpha\beta} \left[ \frac{r}{q} \left( \frac{\pi_L}{\pi_N} \right) - 1 + \delta \right] \quad (7a)
\]

\[
N_{ss} = \frac{\vartheta}{\alpha\beta} \left[ r \left( \frac{\pi_L}{q\pi_N} \right) - 1 + \delta \right] - \frac{\pi_L L}{\pi_N W} + \sqrt{\frac{r\pi_L}{q\pi_N}} \quad (7b)
\]

In the steady state, hunting levels decline with the benefits derived from tourism \((\alpha\beta)\), but increase with the profitability of agriculture, and with the rate of discount, suggesting a higher preference for current consumption (or a longer path of accumulation of natural capital). From expression (5) in the steady state, the combined value of the harvest must equal \(r\left(1 - \sqrt{\frac{\pi_L}{r\pi_N}}\right)\). Using expressions (7a) and (7b) with the equilibrium condition \(\frac{\dot{W}}{W} = 0\), yields the steady state stock of \(W\):

\[
W_{ss} = \frac{\alpha\beta \frac{\pi_L}{\pi_N} L}{2 \left[ \sqrt{\frac{r\pi_L}{q\pi_N}} - r + \frac{\left(\vartheta - \alpha\beta\right) \frac{\pi_N}{\pi_L}}{\vartheta} \right]}
\quad (8a)
\]

where \(\vartheta = \alpha\beta + \eta + \vartheta < 1\) is a measure of the scale parameter of the welfare function.

\(^{11}\)By inspection \(\frac{d(\Omega)}{d(\alpha\beta)} < 0\) and \(\frac{d(\Omega)}{d(\alpha\beta)} < 0\) and \(\frac{d(N)}{d(r)} < 0\) and \(\frac{d(N)}{d(pq)} < 0\) and \(\frac{d(N)}{d(pq)} > 0\) and \(\frac{d(N)}{d(pq)} > 0\) and

\(\frac{d(N)}{d(\Omega)} > 0\) if \(\eta < \frac{L\vartheta}{\omega_L}\).
Expression (8a) reveals that in the steady state, the stock of wildlife will be larger, the smaller the relative profitability of hunting, compared to farming. Conversely, the steady state values of land in the benchmark model are given by:

\[
L^*_{w} = \frac{\alpha\beta \pi_L \phi}{\alpha\beta \phi \pi_N} \frac{L}{2 - q \pi_N [r - (\phi - \alpha\beta) \delta]} \quad (8b)
\]

In the steady state, the optimal level of land allocated to wildlife is positively related to factors that increase their relative payoffs. These results are largely predictable and provide a benchmark for comparison with outcomes under regulatory imperfections.

3. Imperfect Regulation

It is hard to overstate the challenges of regulating an area as large as the Serengeti – an expanse extending over 25,000 km² spanning an international border. Poaching by the local population is a widespread problem, estimated at over 10% of the wildebeest population in certain years (Rentsch op cit). Simultaneously land conversion and encroachment, especially in the buffer zones is a problem that grows more pervasive with rising population densities. This section extends the core model by allowing for breaches of regulatory quotas and possible legal sanctions for poaching and encroachment onto areas reserved for wildlife. There is limited evidence of trophy operators violating their quotas – perhaps a reflection of the large hunting blocks that are leased to operators over significant periods of time together with generous hunting allocations, which are likely more incentive compatible. Allowing violations by trophy hunters in the model would be straightforward, but is ignored in what follows.

With regulatory imperfections the timing of events becomes significant. It is assumed that the government is the first mover and defines the policy parameters, taking account of the downstream responses (the reaction functions) of other agents where relevant. Observing these policies, the local population responds by setting the level of hunting \(N\) and the land allocated to farming \(L_{g}\). Lacking
property rights, the local population ignores resource dynamics and they myopically maximize short term expected utility, given the observed policy parameters. In contrast the government maximizes long term welfare taking account of resource dynamics. Thus the local population maximizes:

\[
\max u = \left( \pi_N W N - \tau \pi_N W (N - N_a)^2 + \pi_L L_g - \nu \pi_L (L_g - L_a)^2 \right) \]

(9a)

where \( N_a \) and \( L_a \) are the legally permissible allocations of hunting and agricultural land determined by the government and \( \tau \pi_N W \) and \( \nu \pi_L \) represent the expected fines which are levied respectively on hunting and farming in excess of these allowable limits.\(^{12}\) Further \( \tau > 0 \) if \( N > N_a \) and \( \tau = 0 \) if \( N \leq N_a \) and \( \nu > 0 \) if \( L_g > L_a \) and \( \nu = 0 \) if \( L_g \leq L_a \). Note that the expected penalty is assumed to be increasing in the misdemeanor, reflecting the common judicial convention that the punishment should fit (rise with) the crime.

Maximizing equation (9a) yields the first-order conditions which define the reaction functions of the local population:

\[
N = N_a + \frac{1}{2\tau} \quad \text{and} \quad L_g = L_a + \frac{1}{2\nu}
\]

(9b)

Observe that \( \forall \infty > \tau > 0, N > N_a \), thus harvest levels will always exceed the allowable quota, by an amount that is inversely proportional to the fine for non-compliance (unless the fine is infinite). This is arguably a realistic feature of the model. If the allowable quota \( (N_a) \) is zero, the fine coincides with a tax levied on the whole amount of hunting. A similar result applies to the land allocation decision.

\(^{12}\) The expected penalty can be interpreted as the product of: the probability of detection (say \( z \)), the probability of conviction conditional upon being detected (say \( c \)) and the penalty once convicted (say \( e \)). Thus \( \tau = zce \). Introducing corruption and bribe giving drives a wedge between the probability and cost of detection and conviction, but does not alter the analysis.
Note that since $0 \leq N \leq 1$, and $0 \leq L_a \leq L_{np}$, fines must meet the conditions: $\tau \geq \frac{1}{2(1 - N_a)}$.

Substitute (9b) in (9a), to define the indirect utility function:

$$V(\Pi) = [\pi_NW(N_a + 1/2 \tau) - \tau \pi_NW(N_a + 1/2 \tau - N_a)^2 + \pi_L(L_a + 1/2 \nu) - \nu \pi_L(L_a + 1/2 \nu - L_a)^2] = \Pi^0 = [\pi_NW(N_a + \frac{1}{4\tau}) + \pi_L(L_a + \frac{1}{4\nu})]^0$$

(9c)

As the first-mover, the government will take account of the downstream responses of agents as defined in the reaction functions in equation (9b). Thus the modified Hamiltonian is given by:

$$H = FW^\sigma \Omega^\psi V(\Pi) + \mu(W - \frac{\nu}{(L-a)} - \Omega W - (N_a + \frac{1}{2\tau})W)$$

(10a)

Since there are two instruments (the fine and the quota) and one objective (the optimal allocation), one of the instruments can be set arbitrarily, while the other is defined through the optimization of equation (10a). In what follows we focus on defining optimal quotas ($N_a$ and $L_a$) taking the expected penalties ($\tau$ and $\nu$) as given. This is perhaps a realistic description of institutional realities. Typically the conservation authorities have limited jurisdiction over criminal sanctions and their authority is restricted to determining issues directly related to wildlife management such as quotas and allocations. The ultimate penalties for violating regulations are usually determined by other layers of government involving the judiciary, over which conservation authorities have little direct control. For policy purposes these parameters are given. The first-order conditions are defined by:

$$\frac{dH}{dN_a} = \frac{\partial U\pi_N}{\Pi} = \mu = 0$$

(10b)

13 For example if the quota on hunting is 5% of the stock of wildebeest, the minimum tax that would yield a value of the actual hunting share not exceeding 100% would be 52% of unit profits. Another interpretation is also possible. Consider, however that the tax is levied such that $\tau_v$ is obtained by equating: $\tau_v\pi_NWN = \pi_NW(N - N_a)^2 \rightarrow \tau_v = \frac{(N - N_a)^2}{N}$. Thus, for example, for $\tau = 50$, $N_a = 0.05$, the optimum value of $N$ would be 0.06 and the marginal ad valorem tax rate $\tau_v = 0.01$. 

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\[ \frac{dH}{d\Omega} = \frac{\eta U}{\Omega} - \mu W = 0 \quad (10c) \]

\[ \frac{dH}{dL_a} = \frac{\partial V L_a}{\pi} - \frac{\mu r W^2}{q(L - \frac{1}{2v} - L_a)} = 0 \quad (10d) \]

\[ \frac{\mu}{\mu} = \delta + (1 - \frac{\sigma}{\eta})\Omega - (N_a + \frac{1}{4\tau}) + (N_a + \frac{1}{2\tau}) - r[1 - \frac{2W}{q(L - \frac{1}{2v} - L_a)}] \quad (10e) \]

Using (9b), (10b), and (10d) the allocation of land is given by:

\[ L_a = L - \frac{1}{2v} - W \sqrt{\frac{\pi M}{\eta N}} \rightarrow L = L - W \sqrt{\frac{r \pi_N}{q \pi_L}} \quad (11) \]

The amount of land allocated to farming increases with the profitability of farming, declines with the stock of wildlife and increases with the carrying capacity of wildlife since the payoffs from wildlife related activities increase with resource abundance. Further note that as \( v \) declines the amount of land allocated to farming also declines.

Using (10c) and (10d) the steady state allocation of trophy hunting is given by:

\[ \Omega_{ss} = \frac{\eta}{\alpha \beta} \left( \frac{r \pi_L}{q \pi_N} - r + \frac{1}{4\tau} + \delta \right) \quad (12a) \]

The numerator of (12a) is analogous to the familiar fundamental equation of renewable resources, with an adjustment reflecting imperfect compliance. As compliance declines, so does the stringency of (optimal) regulations, in recognition of the limits of governance. Hence the optimal allocation to trophy hunting rises. This simply reflects the fact that the optimal stringency of regulations depend upon levels of enforcement.

Turning next to bushmeat hunting, the steady state allocation is defined by:

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14 Note that a greater carrying capacity allows for higher levels of agriculture. Contrary to popular policy wisdom the latter result suggests that policies that diminish ecological carrying capacity need to be accompanied by a reduction in farmed area (intensification), rather than the reverse. Agricultural expansion is often the stated rationale for these policies (e.g. water abstraction or traffic increases) in and around protected areas – which is the opposite of the optimal response implied by this model.
\[ N_a^{ss} = \frac{\theta}{\alpha \beta} \left[ \left(2 \frac{r \pi_L}{q \pi_N} - r \right) + \frac{1}{4 \tau} + \delta \right] + J_1 \]  
\hspace{1cm} \text{(12b)}

where 
\[ J_1 = \frac{r \pi_L}{q \pi_N} - \frac{1}{4 \tau} - \frac{\pi_L L}{\pi_N W} \left(1 - \frac{1}{4v}\right) \cdot \]

The share of bushmeat hunting is:
\[ N^* = N_a^{ss} + \frac{1}{2 \tau} \left(\frac{\theta}{\alpha \beta} \left[ \left(2 \frac{r \pi_L}{q \pi_N} - r \right) + \frac{1}{4 \tau} + \delta \right] + J_2 \right) \]  
\hspace{1cm} \text{(12c)}

where 
\[ J_2 = \frac{r \pi_L}{q \pi_N} + \frac{1}{4 \tau} - \frac{\pi_L L}{\pi_N W} \left(1 - \frac{1}{4v}\right) \]

The equilibrium level of bushmeat hunting includes a non-compliance factor \( J_2 \), which rises as the penalties \( \tau \) and \( \nu \) decline. Intuitively, in regimes with weak penalties, there is less compliance and knowing this the government allows for a higher legal amount of bushmeat hunting, \textit{ceteris paribus}.

Wildlife stocks in the steady state are defined by:
\[ W_{ss} = \frac{\alpha \beta \left[ \frac{\pi_L}{\pi_N} \left(1 - \frac{1}{4v}\right) \right] L}{\left\{2 \frac{r \pi_L}{q \pi_N} - r + \left(\frac{\phi - \alpha \beta}{\phi} \delta + \frac{\phi}{4 \tau}\right)\right\}} \]  
\hspace{1cm} \text{(12d)}

where \( \phi = \alpha \beta + \eta + \beta < 1 \) is a measure of overall convexity of the social welfare function.

Note that a steady state with positive values requires that both the numerator and denominator are positive\(^{15}\).

Land allocated to wildlife in the steady state is
\[ L_{ss} = \frac{\alpha \beta \left[ \frac{\pi_L}{\pi_N} \left(1 - \frac{1}{4v}\right) \right] L}{2 + \left(\frac{q \pi_N}{r \pi_L}\right)^{1/2} \left\{-r + \left(\frac{\phi - \alpha \beta}{\phi} \delta + \frac{\phi}{4 \tau}\right)\right\}} \]  
\hspace{1cm} \text{(12e)}

\(^{15}\)To see why note that the numerator needs to be positive to ensure that shares of hunting are non-negative but less than unity and therefore the denominator needs to be positive.
The following Lemmas summarize and compare the two equilibria. They suggest that the proportion of stock harvested under imperfect regulation is always higher than under perfect regulation (for finite fines) and as a result wildlife stocks are always lower under imperfect regulation. This reflects the inability to fully control harvesting and land use in an environment where compliance cannot be assured. In contrast Lemma 2 asserts that as regulatory compliance improves the amount of land devoted to agriculture declines, since in a better regulated economy it is easier to ensure compliance with regulations. Finally Lemma 3 demonstrates how land allocations need to vary with changes in carrying capacity and relative payoffs.

Let \( \Omega_{ss}^P, \Omega_{ss}^I, N_{ss}^P, N_{ss}^I \) be the proportion of wildlife harvested by trophy hunters and bushmeat hunters respectively under perfect (p) and imperfect (I) compliance in the steady state and let \( W_{ss}^P, W_{ss}^I \) be the respective steady stocks of wildlife. Then:

**Lemma 1a.** With finite penalties the proportion of wildlife harvested under imperfect compliance by trophy hunters and bushmeat hunters, always exceeds the proportion harvested under perfect compliance. That is \( \Omega_{ss}^P < \Omega_{ss}^I \), and \( N_{ss}^P < N_{ss}^I \).

**Proof:** From (7a) \( \Omega_{ss}^P = \frac{\eta}{\alpha \beta} [r(2 \sqrt{\frac{\pi_L}{q \tau N_L}} - 1) + \delta] \) and from (12a) \( \Omega_{ss}^I = \frac{\eta}{\alpha \beta} [(2 \sqrt{\frac{\pi_L}{q r N_L}} - r) + \frac{1}{4 \tau} + \delta] \). Thus \( \Omega_{ss}^P - \Omega_{ss}^I = -\frac{1}{4 \tau} < 0 \ \forall \ 0 < \tau < \infty \). From (7b) \( N_{ss}^P = \frac{\vartheta}{\alpha \beta} [r(2 \sqrt{\frac{\pi_L}{q r N_L}} - 1) + \delta] \frac{\pi_L L}{\pi_N W} + \frac{r \pi_L}{q \pi_N} \) and by (12c) \( N_{ss}^I = \frac{\vartheta}{\alpha \beta} [(2 \sqrt{\frac{\pi_L}{q r N_L}} - r) + \frac{1}{4 \tau} + \delta] + J_2 \). Thus \( N_{ss}^P - N_{ss}^I = -\frac{1}{4 \tau} \left( \frac{\vartheta}{\alpha \beta} + 1 \right) \frac{\pi_L L}{\pi_N W} \left( \frac{1}{4 \nu} \right) < 0 \ \forall \ 0 < \tau < \infty \) and \( 0 < \nu < \infty \). ■

**Lemma 1b.** In a steady state wildlife stocks under imperfect compliance are always lower than under perfect compliance. That is \( W_{ss}^P > W_{ss}^I \).
Proof: From (8a) \( W^p_{ss} = \frac{\alpha \beta \pi L}{\phi} \frac{\pi L}{\pi N} L \) and (12d)

\[
\left[ 2 \left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right) \right].
\]

\( W^l_{ss} = \frac{\alpha \beta \left[ \frac{\pi L}{\phi} (1 - \frac{1}{4v}) \right] L}{\left[ 2 \left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right) \right]} \). Consider first the numerators of these expressions – clearly:

\[
\frac{\alpha \beta \left[ \frac{\pi L}{\phi} (1 - \frac{1}{4v}) \right] L}{\left[ 2 \left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right) \right]} < 0 \quad \forall \quad 0 < v < \infty.
\]

Consider next the denominators:

\[
2 \left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right) \left[ 2 \left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right) \right] = \frac{\phi}{4r} < 0, \quad \forall \quad 0 < r < \infty.
\]

Thus the numerator of (33) is smaller and its denominator larger so that \( W^p_{ss} > W^l_{ss} \).

Note also that the difference in wildlife stocks vanishes only if penalties are infinite. For future discussion of policy issues we note the following properties of the equilibria:

Lemma 2 As regulatory compliance improves the amount of land devoted to agriculture declines.

That is \( \frac{dL_g}{dr} > 0 \) and \( \frac{dL_g}{dv} > 0 \).

Note that using (11) we have \( \frac{\partial L_g}{\partial w} = - \frac{(r \pi N)}{q r \pi L} < 0 \) and from (12d) we have \( \frac{\partial w}{\partial r} = \frac{X}{4r^2(\zeta + \frac{1}{4r})} > 0 \), where \( \zeta = \sqrt{\left( \frac{r \pi L}{q r \pi N} - r + \frac{(\phi - \alpha \beta)}{\phi} \frac{\pi N}{\pi L} \right)} \) and \( X = \frac{\alpha \beta \left[ \frac{\pi L}{\phi} (1 - \frac{1}{4v}) \right] L}{\frac{\partial w}{\partial v}} > 0 \).

Hence \( \frac{dL_g}{dr} = \frac{\partial L_g}{\partial w} \frac{\partial w}{\partial r} > 0 \) and \( \frac{dL_g}{dv} = \frac{\partial L_g}{\partial w} \frac{\partial w}{\partial v} > 0 \).

Thus the optimal allocation of land for conservation is larger in situations with greater compliance.

Intuitively in situations of weak governance, stricter regulations (limits on agricultural expansion) cannot be enforced. Recognizing this, where compliance is weak a greater amount of land is devoted to agriculture. It is interesting to note that this result emerges even without incorporating monitoring costs in the model.
Lemma 3 As carrying capacity declines the optimum steady state allocation of land to wildlife increases and as the relative payoffs to hunting increase the optimum steady state allocation of land to wildlife declines. That is \( \frac{\partial L_{ssw}}{\partial q} < 0 \) and \( \frac{\partial L_{ssw}}{\partial \pi_N} < 0 \).

Proof. From (12e) \( \frac{\partial L_{ssw}}{\partial q} = -\frac{\alpha \beta \phi}{2} \frac{q^2}{(\pi_{\pi_{L}})^2} < 0 \); where \( B = \left\{ \frac{\phi^4}{4T} - r + \frac{(\phi - \alpha \beta)}{\phi} \delta \right\} \) and upon simplifying \( \frac{\partial L_{ssw}}{\partial \pi_N} = -\left( \frac{\pi_{L}}{\pi_{N}} + \frac{Bq}{2r \pi_{N} (\pi_{L})^2 \left( \frac{q \pi_{N}}{\pi_{L}} \right)^2 + 2} \right) < 0 \).

In policy terms Lemma 3 seems especially instructive. Activities that lower carrying capacity \( (q) \) call for an increase in land allocated to wildlife – often the reverse of what is observed. Intuitively as \( q \) increases (decreases), wildlands become more (less) productive, so any given payoff from \( W \) can be obtained with less (more) land devoted to wildlife.

4. Partial Equilibrium Simulations

This section numerically simulates the impacts of key pressures, individually and in combination to assess the response of agents in the model. As noted in Section 1 the model is parameterized for the Serengeti given the availability of data for this biome and changes in the surrounding areas. We consider the consequences of changes in carrying capacity.\(^{16}\)

This section seeks to assess the possible bio-economic implications of such activities. In terms of the model parameters, policies to boost agricultural production would increase payoffs and incentives to expand the agricultural frontier into former wildlands, with implications for wildebeest numbers, tourism and hunting. Other proposals, which typically involve use of the ecosystem for other purposes are expected to lower the carrying capacity of the ecosystem, especially if they impede the wildebeest

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migration which helps sustain the high density of ungulates. \textsuperscript{17} As a keystone species, declining wildebeest numbers would have cascading impacts on the abundance and diversity of other species. In what follows we explore the consequences of such changes sequentially and in combination and assess the effectiveness of regulatory instruments in mitigating the consequences.

Appendix 1 provides a summary of the assumed parameter values used to calibrate the model. Figure 1 illustrates the equilibrium which occurs at the ascending branch of the logistic growth curve. For the given parameters the harvest function intersects the growth curve from below, implying that this equilibrium is stable. Figure 1 also illustrates the impacts of a change in carrying capacity ($q$). Observe that as carrying capacity increases (or declines) the corresponding off-take rises (or falls) less (more) rapidly due to the higher curvature of the logistic curve near the origin (i.e. its concavity). The economic implication is that a declining carrying capacity rapidly erodes the economic benefits accruing to the wildlife harvesters and vice-versa.

The results of the simulation are in Table 1. The first column summarizes the baseline case which attempts to describe the current situation. The simulation tracks observed outcomes with reasonable accuracy. In the baseline the model predicts about 1.12 million wildebeest in the steady state which corresponds closely to an actual population of between 1.2 - 1.3 million animals. The projected hunting off-take at 300,000 is somewhat larger than the estimated harvest of 200,000, perhaps

\textsuperscript{17}A decline in numbers could be due to restrictions on the ability of wildebeest to track temporal shifts in high-quality forage resources across the landscape. In the most rigorous quantitative assessment available, Holdo \textit{et al} (2011) find that habitat fragmentation resulting from such structures (even without habitat loss), would lead to a projected median decline of 38 percent of the population.
reflecting the clandestine nature of much hunting, while projected tourist numbers at 282,000 are within the estimated current range of between 200,000 and 300,000 visitors a year.

Consider first the effects of a decline in \( q \), the carrying capacity, which could occur for a number of reasons (examples include the numerous intrusive structures suggest that would impede the migration, high intensity tourism, mining or other pressures). We begin by considering the effects of a 20% decline in carrying capacity, which is lower than the median prediction of Holdo et al (op cit) for current policy pressures.\(^{18}\) As noted in the previous sections the optimal response to a lower carrying capacity calls for an increase in the allocation of land to wildlife and a reduction in hunting quotas. Despite these policy shifts, wildlife numbers decline by about 22% to 850,000 and tourist numbers fall. The next column explores the effects of a 20% increase in agricultural revenues so that the allocation of land to agriculture is increased. Once again wildlife numbers decline by about 25% to 810,000, with a corresponding fall in tourist numbers and the wildebeest harvest.

The next column considers the combined effects of 20% higher agricultural profits together with a 20% decline in the carrying capacity. This time there is a much more dramatic decline in wildebeest numbers (by about 50%) to 600,000 together with an equally significant reduction in the hunting off-take and tourist numbers by almost 30 percent. The implication is clear. The combined pressures have synergistic effects, with one factor exacerbating the effects of the other, so that the joint effects exceed the sum of the individual impacts.

Could these negative consequences be reversed through improved enforcement? The final column considers the optimistic, though unlikely, case where all fines are doubled. While there is some improvement in wildebeest numbers, the decline in the population is still significant at 32 percent. Evidently though increasing penalties may lead to improved compliance, this does little to address the root cause of the decline in wildlife numbers - a lower carrying capacity resulting from a degraded ecosystem.

These results have two striking implications for policy. First there is a need to be alert to potential synergisms, which may lead to unwelcome surprises when multiple impacts interact. Second the

\(^{18}\) The detailed simulations by Holdo et al (op cit) based on a spatially explicit model suggest a median population decline of 38%. To guard against exaggerating possible impacts we consider a more modest reduction in carrying capacity.
standard policy instruments – fines and enforcement of quotas – may do little to reverse the population decline when the carrying capacity and hence productivity of the ecosystem is diminished. This might suggest the need to avoid damage in the first instance if the economic gains outweigh the foregone benefits. To explore these trade-offs in greater detail the following section examines wider economic impacts in a general equilibrium context. It does this by embedding the bio-economic results into a CGE model.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>20% Reduction in carrying capacity</th>
<th>20% increase in agricultural profits</th>
<th>Combined 20% increase in ag. profits and 20% reduction in carrying capacity</th>
<th>Combined + Doubling of fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wildebeest (#)</td>
<td>1,120,000</td>
<td>855,000</td>
<td>810,000</td>
<td>600,000</td>
<td>740,000</td>
</tr>
<tr>
<td>Harvest (#)</td>
<td>300,000</td>
<td>210,000</td>
<td>200,000</td>
<td>140,000</td>
<td>180,000</td>
</tr>
<tr>
<td>Tourists (#)</td>
<td>289,000</td>
<td>260,000</td>
<td>240,000</td>
<td>200,000</td>
<td>210,000</td>
</tr>
<tr>
<td>Land to wildlife (km²)</td>
<td>17,300</td>
<td>17,600</td>
<td>16,900</td>
<td>17,200</td>
<td>18,100</td>
</tr>
</tbody>
</table>

5. General Equilibrium Simulations

This section outlines the results of a CGE simulation. At the core of this CGE is a social accounting matrix (SAM), whose architecture reflects the main components of the Tanzanian economy. The information for the SAM is drawn from the GTAP data base which is augmented with other data to extend the natural resource component of the model. A detailed description of the data and model is in the Appendix. A CGE approach seems warranted in this context given the size of tourism and wildlife sector and the importance of the Serengeti to the national economy of Tanzania. Tourism is the second largest source of foreign exchange, estimated at over US$1.28 billion, and directly contributes to more than 13 percent of GDP, with a considerably higher indirect contribution (World Travel and Tourism Council, 2013). The overwhelming majority of benefits derive from tourist visits to the Serengeti – one of the primary attractions. Additionally the government earns significant revenue from fees and licenses for tourism and trophy hunting estimated at close to $100 million a

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19 This has implications for the way infrastructure impacts are managed. It is not unusual to seek payments for damage to the environment with the revenues being used to improve enforcement of regulations. This result suggests this strategy could be ineffective.

20 Cataldo Ferrarese, of the University of Rome “Tor Vergata”, collaborated and provided expert research assistance for the construction of the CGE model.
A CGE approach is also useful in that it provides a consistent framework to assess the overall
and distributional impacts of trade-offs between segments of the economy – such as ecosystem and
environmental losses in the Serengeti that occur as a consequence of gains in other parts of the
economy (e.g., agriculture, mining and so on).

To our knowledge the introduction of wildlife in a CGE is somewhat novel feature of this paper and
warrants a brief explanation. For renewable natural resources such as wildlife, the accounting in the
CGE-SAM can be done in a manner that is similar to the treatment of livestock, with the important
difference, that there is no investment in producing the asset when appropriate conditions prevail. If
the population under consideration grows (or declines), any change in the stock of animals, will be
credited to the capital account. Of course in a steady state the population (stock of capital) is constant
– if one eschews the question of different vintages.

The CGE model outlined in the Appendix is solved under the following macroeconomic closure and
market clearing conditions: (i) the exchange rate is flexible and the balance on the current account is
fixed, so that the exchange rate adjusts to clear the current account; (ii) the internal balance –
government savings – is fixed, as are all tax rates except the income tax rates paid by households,
which adjust to clear the government account; (iii) the volume of investment is fixed, i.e., the capital
stock passed onto the next year is fixed, implying that household savings rates adjust to clear the
capital account; and (iv) the market clearing condition for the factor markets are for long run
adjustment so that capital and labor are assumed to be mobile across activities in response to changes
in wages or rental rates.

Table 1 in the Appendix presents simulations for the cases considered in the partial equilibrium
analysis where there are losses in the wildlife sector and benefits accruing in agriculture and
connectivity. This simulation closely corresponds to current priorities. The appendix also presents
simulations, for carrying capacity changes of 25% and 15%, with all else remaining the same in the
economy. The basic qualitative results are unchanged. In the simulations it is assumed that

21 See http://www.mof.go.tz/mofdocs/overarch/strategicplan.doc
agricultural profits (economy-wide) rise by 20% and connectivity costs decline through the economy by 15%, while there is a reduction of carrying capacity of 20%. Simulations of other scenarios are in the Appendix and broadly reflect the finding of this particular illustration. To guard against exaggeration of impacts the assumed benefits from the proposed changes in the Serengeti are considerably higher than suggested gains, while assumed impacts on carrying capacity is lower than suggested by recent demographic models. These changes would result in a reduction of proceeds from international tourists of $552 million per year (tourist numbers go from 750,000 to 515,000, expenditure per day is $200 with 10 days average stay). To guard against exaggerate tourist expenditures are significantly underestimated. Data reported in the World Travel and Tourist Council suggest expenditures of about $500 per day in Tanzania.

As the table shows, in all the simulations, the effects appear to be diffused through the economy. However impacts are especially large among (poor) rural households. Even in a case when there is a very large positive shock on agriculture, to compensate for a loss of bushmeat, there is a net loss registered in the rural sector as a result of economic contraction following the reduction of foreign exchange flows. Value added (a proxy for GDP), on the other hand, changes by more than the flow of tourists revenue due to changes in the exchange rate. These exchange rate changes imply that the effects of tourism are spread across the economy. In short the simulations suggest that policies that lower or increase revenues and benefits from the Serengeti have wide ranging impacts that spill over to other sector of the economy. Understanding the direction and magnitude of these spillovers is crucial to policy analysis.

6. Conclusions

This paper has developed a bioeconomic model linked to a CGE model to assess the economy-wide consequences of alternative policies. The bioeconomic model characterizes optimal policies and suggests how actual responses may depart from optimal policies. Simulations in a partial equilibrium

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22 The assumed are far above what is suggested by proponents and considerably higher than what estimates suggest might eventuate (see GoT 2011 and Holdo et al 2011)
context indicate that synergism (super-additivity) of impacts must remain a source of concern. Each threat when considered in isolation is less significant than the combined impacts of pressures, so that the total impact is greater than the sum of the individual effects. This suggests practical and conceptual challenges for policy making which typically considers impacts and issues separately and by sector. For instance debates on the volume and impact of tourism and tourist infrastructure, seldom consider effects emanating from the agriculture and land-use, or connectivity and vice-versa. Moreover the analysis finds that the conventional instruments of conservation policy (fines, quotas, etc) are less effective in reversing the damage once carrying capacity has been impaired.

The CGE analysis suggests that economic impacts that eventuate from changes in tourism and bushmeat hunting in the Serengeti have diffuse economy-wide impacts that outweigh (by orders of magnitude) the effects of the alternative activities considered. To guard against overstatement, ecosystem impacts (such as tourism revenues) are undervalued. These results appear to indicate that linkages to the natural resource sector (backward and forward multipliers) are important and neglecting these may lead to underestimates of the economic significance.

There are of course a number of caveats and limitations of the analysis that need to be considered in future research. First it would be useful to develop a regional and spatially differentiated CGE and SAM, though this would be a large and resource intensive exercise. Additionally the bioeconomic model could also need to be enriched by including labor supply in the household decision making. Our preliminary analysis suggests that this adds algebraic complexity without changing the key results (summarized in Lemmas 1 – 3). Finally the biological model could be improved by adding a stochastic component to represent population dependence on rainfall, climate change as well as predator-prey dynamics other forms of species interactions.
References


Kiddegheshe, 2006 Who Pays for Wildlife Conservation in Tanzania http;dlip.indiana.edu/dic


Appendix 1 Model Calibration

| Total Serengeti Mara ecosystem (Sinclair et al 2008) | 25000 km |
| SNP (Sinclair et al 2008) | 14,763 |
| Ngorongoro Conservation Area (Sinclair et al 2008) | 8,288 |
| Maswa Game Reserve (Sinclair et al 2008) | 2,200 |
| Mara Reserve (Sinclair et al 2008) | 1,672 |
| A (derived see footnote 7) | 6.006 |
| α β (derived) | .8 |
| δ (assumed) | 0.05 |
| πL/πN (derived see below) | 0.3 |
| Φ (assumed) | 0.91 |
| q(max) (derived below and using Stratton 2012) | 100 per km² |
| r (Stratton 2012) | 0.18 |
| πL (Serengeti.org) | $400 per km² |
| τv (derived using footnote 13) | 0.25 |
| νv (derived using footnote 13) | 0.5 |

It is useful to recall that we find that a non negative value of wildlife growth requires: $q \geq \frac{\pi_L}{r\pi_N}$ if $L_g \leq L_{np}$ and $L_w = L_{np}$ otherwise. Further the ratio between agricultural and hunting profitability is based on the following units of measure $\frac{\pi_L}{\pi_N} = \frac{\partial \Pi / \partial L_g}{\partial \Pi / \partial (NW)} = \frac{NW}{L_g}$. The reproduction rate of 1.8 is from Stratton (2012). Suppose that bushmeat hunting is around 60,000 wildebeest per year and the maximum allocation of agricultural land is about 500,000 has, the ratio between land and poaching profits is about 0.12. With a reproduction rate of r=0.18, this implies that the (maximum attainable) value of $q$ must be greater than or equal to 66 animals per km (or 0.66 per ha) of wild land, or about 1.4 times the present ratio of 0.5 (i.e. 1.2 million wildebeest on 2.5 million has of national park land). In turn, this means that the maximum carrying capacity of about 1.65 million, which is close to the estimate of the carrying capacity in Stratton (op cit).

Appendix 2 Description of SAM and CGE Multipliers

The model is based on a SAM estimated on the basis of the GTAP data set supplemented by official and other statistics. The basic model represents the Tanzanian economy with 10 economic sectors, 4 production factors, 2 institutions, Capital Formation and The Rest of the World, or, in more detail:

Our model represents the economy with 29 sectors. In the GTAP model the Natural Resources sector only includes the value of the resources used by mining and extraction. The factor Land includes only cultivated land. The GTAP SAM is augmented in to take better account of the Serengeti economy:
The Masai represent over 1 million of Tanzania’s rural population and 4.5% of rural household. In the model we hypothesize that the Masai consumption pattern is analogous to that of other rural households.

The value of tourism in 2010 is 1.3 billion US Dollars (source World bank database) and represent 20% of total export. The sources of data are the National Statistic Bureau and the World Bank database. The international tourist arrivals in Tanzania were 783,000 in 2010 and, on the basis of a large survey of tourist expenditure, it is estimated that Tanzania earned US $1.23 billion in 2008, out of which US $160 million were from tourists to Zanzibar. The survey results show that the overall average expenditure for holiday visitors who came under package arrangement was US $209 per person per night, while that of non package was US $186 per person per night. The average length of stay for visitors to the United Republic of Tanzania was 10 nights. The domestic tourist numbers in 2008 are 639,749 with 280,000 going to National Parks of which 221,000 went to the Ngorongoro crater. The rest visited museums and other sites. The value of the domestic tourism expenditure for entrance to the attraction areas are estimated at about $500,000 per year. In the model this value is related with the Dar es Salaam Household and other urban households.

Travel motivation to Tanzania is wildlife, hunting and trekking for over 70% of international tourists, beaches for 14%, a combination of the two for 10% and culture for 5% (Ministry of Natural Resources and Tourism). We assume that 85% of tourism value is in the Park tourism sector and 20% Beach and Cultural Tourism.

Hunting

The animal population is estimated in 1.3 millions (wildebeest, zebras). The value of the sector in the SAM model represents their “use value” for Tanzanian economic sectors, households and other institutions.

The value of household consumption of biodiversity (mainly by the Masai) represents legal and illegal hunting on the part of residents. According to an estimate by Campbell, Nelson and Loibooki, the animals killed by illegal hunting were 86,400 in 2000. The revised estimates that we use for 2010, including legal and illegal hunting by residents, is about 102,000 animals per year. This is likely a large underestimate according to popular commentary. The value of a single animal killed will change according to the different scenarios, as it will depend on willingness to pay, GDP, composition of the kill among other things (Scandizzo and Cufari, 2013). In particular, we assume a value of $300 per animal in the base case which is the average value of a domestic cow in the Tanzania LSMS household survey.

A negligible part of hunting is assigned to other rural households sector.

Trophy hunting for park tourists

Annually over 90,000 people visit Serengeti and based on reports (Serengeti.org) we assume that 45% of these do so to hunt. The average daily cost per person in a safari is $500, so that the value estimated of park tourism use of animal biodiversity for an average 5 day safari is 112.5 million USD. The average costs for a 10 day hunting license is $950 (Tanzanian Government Fee). This is presumed to be a significant underestimate as recording of trophy hunting is incomplete a feature that is widely encountered in other rent-rich sectors.

Savanna and forest habitat

We assume that the Masai use 10% of the total area of Serengeti for agriculture. Using an average value of hectares equal to 100 USD the value of Savanna and Forest habitat in Masai is 18 usd million.

Other sector related with the forest habitat are Agriculture, Mining & Extraction, Processed Food Labor-Intensive Manufactures, Capital-Intensive Manufactures, Utilities and Construction and other rural Households.

The table below reports the results of our estimation of the Social Accounting Matrix for Tanzania for the year 2010.

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23 Sustainable use of Wildland Resources (2001)
### Table A2. CGE Simulations (million US$)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>20% Reduction in carrying capacity and 15% fall travel costs</th>
<th>20% increase agricultural profits 15% fall travel costs</th>
<th>Combined 20% reduction in carrying capacity, 20% increase in ag profits, 15% fall travel costs</th>
<th>Double Fines with 20% reduction carrying capacity, 20% increase ag. profits, 15% fall travel costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest (Value in M$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>409.31</td>
<td>265.31</td>
<td>141.48</td>
<td>292</td>
<td></td>
</tr>
<tr>
<td>Tourism (Value in M$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>578</td>
<td>458.28</td>
<td>427.21</td>
<td>285.56</td>
<td>341.52</td>
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</tr>
<tr>
<td>Value Added (M$)</td>
<td>26,461</td>
<td>25,233</td>
<td>25,451.23</td>
<td>24,429.4</td>
<td>24,946.44</td>
</tr>
<tr>
<td>Change in Value Added (M$)</td>
<td>-</td>
<td>-1,227.37 (-4.6%)</td>
<td>-1,009.77 (-3.8%)</td>
<td>-2,031.60 (-7.7%)</td>
<td>-1,514.56 (-5.7%)</td>
</tr>
<tr>
<td>Urban Households (Change in M$)</td>
<td>-434</td>
<td>-375.9</td>
<td>-730.5</td>
<td>-546.4</td>
<td></td>
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<tr>
<td>Rural Households (Change in M$)</td>
<td>-763</td>
<td>-666.3</td>
<td>-1,278.5</td>
<td>-943.8</td>
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</tbody>
</table>

In the simulations in A2 it is assumed that agricultural profits (economy-wide) rise by 20% and connectivity costs decline through the economy by 15%, while there is a reduction of carrying capacity of 20%. Simulations of other scenarios are in the Appendix and broadly reflect the finding of this particular illustration. To guard against exaggeration of impacts the assumed benefits from the proposed changes in the Serengeti are considerably higher than suggested gains, while assumed impacts on carrying capacity is lower than suggested by recent demographic models. These changes would result in a reduction of proceeds from international tourists of $552 million per year (tourist numbers go from 750,000 to 515,000, expenditure per day is $200 with 10 days average stay). GDP changes by 7%.

**Further Simulations for a 15% and 25% Fall in Carrying Capacity**

<table>
<thead>
<tr>
<th>Reduction in carrying capacity</th>
<th>25%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>-31,856</td>
<td>-16,442</td>
</tr>
<tr>
<td>Labor</td>
<td>-235,473</td>
<td>-112,752</td>
</tr>
<tr>
<td>Capital</td>
<td>-209,57</td>
<td>-98,5808</td>
</tr>
<tr>
<td>Non renewable natural resources</td>
<td>-6,39634</td>
<td>-3,12785</td>
</tr>
</tbody>
</table>

---

24 The assumed are far above what is suggested by proponents and considerably higher than what estimates suggest might eventuate (see GoT 2011 and Holdo et al 2011)
<table>
<thead>
<tr>
<th>Category</th>
<th>Savings 1</th>
<th>Savings 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bush Hunting</td>
<td>-0.9658</td>
<td>-0.49155</td>
</tr>
<tr>
<td>Trophy Hunting</td>
<td>-30.9144</td>
<td>-16.7266</td>
</tr>
<tr>
<td>Savanna and Forest habitat</td>
<td>-2.63916</td>
<td>-1.30501</td>
</tr>
<tr>
<td>Emissions</td>
<td>-0.66305</td>
<td>-0.27004</td>
</tr>
<tr>
<td>Agriculture</td>
<td>-181.976</td>
<td>-93.9374</td>
</tr>
<tr>
<td>Mining &amp; Extraction</td>
<td>-63.3495</td>
<td>-30.9783</td>
</tr>
<tr>
<td>Processed Food</td>
<td>-173.674</td>
<td>-87.7371</td>
</tr>
<tr>
<td>Labor-Intensive Manufactures</td>
<td>-38.0343</td>
<td>-19.6449</td>
</tr>
<tr>
<td>Capital-Intensive Manufactures</td>
<td>-27.7367</td>
<td>-13.2987</td>
</tr>
<tr>
<td>Utilities and Construction</td>
<td>-53.1282</td>
<td>-25.9805</td>
</tr>
<tr>
<td>Transportation &amp; Communication</td>
<td>-188.168</td>
<td>-69.794</td>
</tr>
<tr>
<td>Private Financial &amp; Other Serv</td>
<td>-115.079</td>
<td>-59.9747</td>
</tr>
<tr>
<td>Park Tourism</td>
<td>-477.184</td>
<td>-258.186</td>
</tr>
<tr>
<td>Beach and Cultural Tourism</td>
<td>-88.6355</td>
<td>-48.0243</td>
</tr>
<tr>
<td>Public Services</td>
<td>-36.5007</td>
<td>-18.0473</td>
</tr>
<tr>
<td>Dwelling</td>
<td>-42.1911</td>
<td>-20.2922</td>
</tr>
<tr>
<td>Dar es Salaam region Households</td>
<td>-99.4805</td>
<td>-47.3408</td>
</tr>
<tr>
<td>Other urban Households</td>
<td>-162.44</td>
<td>-77.6345</td>
</tr>
<tr>
<td>Rural Households</td>
<td>-251.306</td>
<td>-122.072</td>
</tr>
<tr>
<td>Masai</td>
<td>-9.00539</td>
<td>-4.49052</td>
</tr>
<tr>
<td>Taxes and Government</td>
<td>-13.5083</td>
<td>-6.7957</td>
</tr>
<tr>
<td>International Tourists</td>
<td>-550</td>
<td>-300</td>
</tr>
<tr>
<td>Natural Capital</td>
<td>-103.062</td>
<td>-51.4817</td>
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</tbody>
</table>