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and Development Projects (ICDPS)? Simulation Results From the
Serengeti Ecosystem

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HOW LONG UNTIL CRISIS IN AFRICAN WILDLIFE INTEGRATED
CONSERVATION AND DEVELOPMENT PROJECTS (ICDPS)?
SIMULATION RESULTS FROM THE SERENGETI ECOSYSTEM

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ABSTRACT

This paper develops a model coupling species population dynamics with endogenous human consumption and poaching behavior in an environment of imperfect labor and product markets and static agricultural production technology subject to environmental shocks. Using the case of the Serengeti, we then simulate how integrated conservation and development projects (ICDPs) might effectively serve as a delaying tactic against biodiversity loss until a more durable solution can be found to the challenge of wildlife conservation in the midst of endemic rural poverty.
Integrated conservation and development projects (ICDPs) have been heavily promoted in recent years, portrayed as "the vanguard of what will undoubtedly be a broad array of initiatives attempting to link conservation and development" [5, p. 577]. ICDPs' "aim to achieve their conservation goals by promoting development and providing local people with alternative income sources that sustain rather than threaten the flora and fauna in natural habitats" [12, p. 27].

ICDPs involve quasi-contractual arrangements wherein residents of communities on the periphery of a protected area surrender access to, or curtail illegal offtake of native species and their habitats in exchange for alternative sources of income and sustenance. We applaud ICDPs' explicit recognition of the interdependence of human and nonhuman species, but we doubt the viability of contemporary ICDP designs, which generally proceed from untested biological and economic assumptions [3].

In many settings, such as the Serengeti, the distribution of game meat from managed harvests is perhaps proposed as a substantial component of the contractual compensation available to rural residents in an ICDP [11]. This points to a central problem in wildlife ICDPs; at some time the protected area manager (PAM) will likely will have to choose between breaching the contract in order to maintain a minimum sustainable herd, or to allow harvesting beyond the...
minimum sustainable herd size in order to honor the ICDP contract with the human community, thereby threatening collapse of the biotic community of interest. This biologically, politically, and socially perilous decision point is what we mean by "crisis."

In the spirit of constructive criticism, we claim that despite their conceptual appeal, "ICDPs are not yet analytically or empirically sound approaches . . . ICDPs must be regarded as no more than short-term palliatives in a longer term struggle to refocus attention and resources on parallel processes of rural development, poverty alleviation and wildlife conservation" [3, pp. 1080-1]. What appear to be reasonable approaches to incentive-based conservation in the short run may be of limited long-run effectiveness as long as agricultural production technologies and market conditions remain static. In this paper we estimate how long ICDPs might effectively delay biodiversity loss until a more durable solution is found to the challenge of wildlife conservation in the midst of endemic rural poverty. Alternately put, how long until crisis in African wildlife ICDPs?

I. Background on Wildlife and the Serengeti Regional Economy

The Serengeti ecosystem covers some 25,000 km² in northern Tanzania and southern Kenya, a region defined by the wildebeest's migratory range. Tanzania's Serengeti National Park, initially established in 1929 as a game reserve, now comprises more than half the ecosystem's land area. It was one of UNESCO's first World Heritage Sites and it is part of one of the world's largest Biosphere Reserves. The Serengeti contains the world's largest herds of ungulates and extraordinary biodiversity, including at least 69 species of large mammals and 517 species of

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2This section relies extensively on information presented in Sinclair and Arcese [16] and Sinclair and Norton-Griffiths [19].
The Serengeti lies on the high interior plateau of East Africa, with sharp seasonal patterns in rainfall and volcanic soils. The spatial and temporal heterogeneity of the environment, which underly the herbivore migrations that organize the ecosystem, makes the Serengeti one of the world's most unique and valuable natural resources.

The ecosystem has experienced significant perturbations this century. Ungulate populations, especially of buffalo and wildebeest, declined dramatically following the introduction of rinderpest in the 1880s and then grew sharply once rinderpest was eliminated from the region in the early 1960s. Most recently, there has been rapid growth in human settlements, especially along the western boundary of the park. Depending on how closely one draws the border around the park, the human population of the Serengeti region comprises 1-2 million people, and has been growing at about 3.0% annually, roughly equal to the national 1980-93 average of 3.2% [23]. This has led to a dramatic increase in the number of poachers. Indeed, Sinclair [15, p. 24] argues that "the illegal killing of the migrant ungulates by poachers is potentially the most serious threat to the Serengeti system. Since the migration determines the structure and function of the system, overharvesting of the migrants with a collapse of their populations will result in the collapse of the whole system." This paper focuses on this crucial issue of human predation on and consumption of wildebeest, the Serengeti's keystone species.

The primary reason for wildlife poaching in the Serengeti is endemic poverty. The World Bank [23] lists Tanzania as the world's poorest nation, with a per capita income of just US$90 in 1993. The economies of the human communities on the periphery of the Serengeti are heavily agricultural. The World Bank's [22] most recent estimates indicate that 59% of Tanzanian agriculturalists fall below Tanzania's poverty line of TSh31,000 (about US$150) annual income.
per capita. Moreover, poverty in the Serengeti region is found to be more widespread and severe than the national average, with Mara region (on the park's western boundary, where most poaching occurs) showing per capita income of only TSH 9380 (US$46) in 1991. Food represents 77% of rural households’ expenditures, divided almost evenly between home production and market purchases. Meat, which comprises only 14% of total food expenditures, is the least likely food group to be consumed out of own production, and “killing wildlife for meat is the most serious form of poaching now occurring in the Serengeti” [1, p. 529]. Poaching in the Serengeti appears to be largely a natural response of poor people teetering on the brink of nutritional catastrophe.

The Serengeti Regional Conservation Strategy (SRCS) is an ICDP just underway in the region [11]. Like many African wildlife ICDPs, SRCS aims to improve protected area management through several channels, of which a primary one is the distribution to villages of carcass quotas through managed harvests. It is too early to assess the results of SRCS game cropping, but we offer the simulation below as a suggestive exercise. Our concern is that “although the legalization of harvesting wildlife outside the park and the setting of quotas for villages looks reasonable in the short term, there remains the question of whether the harvest can be controlled within sustainable limits in the long term” [17]. Our basic finding is that as long as agricultural production technologies and market conditions in the region remain static, ICDPs with an important game cropping component are unlikely to avert crisis, and may even hasten it.
II. Modeling Wildebeest Supply and Demand in the Serengeti

IIa. Noncatastrophic Harvest Volumes

The Serengeti is one of the world’s most carefully studied ecosystems, and its keystone species, the wildebeest (*Connochaetes taurus* Burchell), is one of the most studied ungulates. We adopt the most current available population dynamics model, developed by Pascual and Hilborn (PH) [13], to describe the population dynamics for wildebeest.

\[
N_{t+1} = [N_t S_w^8 S_{dt}^4 + N_t R_t] e^{u_t} - H_t
\]

Equation (1) details the dynamics of \( N_t \), the number of adult wildebeest in the population at time \( t \). Population is stochastically related to \( S_w \), the discrete monthly adult survival rate during the 8 wet season months, \( S_{dt} \), the discrete monthly adult survival rate during the 4 dry season months, and \( R_t \), the number of individuals added to the adult population per capita (the “recruitment rate”) in time \( t \), which encompasses both pregnancy and calf survival rates.

Following PH, we set \( S_w = 0.99 \) based on Sinclair [14]. Demographic stochasticity enters through shocks, \( u_t \), which are independent and identically distributed \( N(0, 0.007) \). Population is reduced by harvest volume, \( H_t \).

Dry season survival and the recruitment rates vary with current environmental conditions. Recruitment and survival rates are both increasing functions of per capita food availability, \( F_t \), which is itself an increasing function of both area, \( A \), and monthly grass production, \( G_t \). \( G_t \) varies directly with average monthly dry season rainfall, \( NR_t \). Equations (2)-(5) capture these relationships.
We follow PH's specification for equations (1)-(5) in simulating the available noncatastrophic harvest volumes. This includes employing Sinclair et al.'s [18] estimates of $\psi = 0.98$ and $\delta = 2.85$. The random variables in the model are thus monthly dry season rainfall, $N_{R_t}$, and the demographic stochasticity term, $u_t$. Furthermore, we employ PH's joint posterior probability distribution for the Bayesian estimates of $\alpha$ and $\beta$ (PH's Table 2) [13]. Thus $\alpha$, $\beta$, $F$, $G$, $N_R$, $S_d$, and $u$ all vary over time, creating population dynamics described in detail by PH. We set a starting value of $N_0$ at 1.0 million animals, an intermediate number between recent wildebeest population estimates ranging from 0.9-1.2 million. Harvest, $H_t$, is determined by human demand, as detailed in the next section.

The parameterized wildebeest population model thus takes the form:

\begin{align*}
S_{d_t} &= \frac{\Psi(F_t, \delta)}{\Psi(F_t', \delta)} \\
R_t &= \beta \cdot \alpha F_t \\
F_t &= \frac{(G_m/30)}{N_t} \\
G_t &= h(N_{R_t}) \tag{5}
\end{align*}

While we retain PH's MA(4) structure for $N_{R_t}$, we use a single scenario, based on mean monthly dry season rainfall over the 1960-89 period of 149.3 mm. PH use three different scenarios for average new rainfall (100, 150, and 200 mm/month).
The time path of $N_t$ permits estimation of the maximum noncatastrophic harvest volume each period, $H_t^*$, based on an estimated critical population threshold of 250,000, the lowest on record, just as rinderpest was eliminated. Thus, $H_t^* = N_t - 250000$. This provides the supply side of the game meat distribution from the PAM to the human communities on the protected area’s periphery.

The best available data suggest meat comprises approximately 14% of food expenditures, or about 11% of total household expenditures, among rural Tanzanians generally [22], implying per capita meat expenditures of about Tsh1,040 (roughly US$5) per year in the Serengeti region. Assume $\frac{1}{4}$ of a Serengeti household's meat consumption comes from game, perhaps a conservative assumption given that meat from domestic stock is far more expensive. Then an average household of seven persons that takes 60% of game meat in the form of wildebeest consumes about $\frac{1}{3}$ wildebeest per year, based on $16/carcass 1988$ fresh game meat prices.
This implies about 60,000 wildebeest currently taken annually in the region, a figure consistent with expert estimates based on discussions with villagers and studies of carcasses. At a metabolic weight of 53 kg, a crude estimate of annual slaughtered wildebeest meat supply in the local Serengeti economy is 3.2 million kilograms. Game meat consumption is substantial and poaching represents an important activity for peripheral communities.

While the population dynamics of the wildebeest is reasonably well understood, little is known about the nature and dynamics of human demand for wildlife. This section is therefore speculative. We model human demand for and poaching of wildlife using the best of the very limited available evidence on the appropriate parameters, but our results are merely suggestive, not proper "empirical" findings. At a minimum, this section and the next should illustrate the pressing need for careful empirical research to estimate the appropriate human behavioral parameters more precisely. To date, studies of wildlife harvest invariably assume exogenous and static demand and labor patterns. This section points toward a more realistic and informative approach to modeling game meat consumption and poaching behavior but one that demands more empirical research for its validation.

Following closely DeJanvry et al.'s seminal work on nonseparable household modeling, we posit a representative Serengeti region household that allocates its labor and land between two different activities, sedentarized food production and poaching, so as to maximize the utility it derives from the consumption of several different goods and of leisure time. Our model captures the essence of the decisions made by agriculturalists operating in an environment

4"Metabolic" weight refers to the mass of muscle, organs, and blood and is, thus, closer to the weight of the meat than the animal's gross weight, including bone, skin, and stomach.
of stochastic production and significant market failures. This permits us to study the nature and time path of human behaviors associated with both poaching and game meat consumption among the human communities on the Serengeti's perimeter.

The household produces \( (q_i \geq 0) \) traditional foods (crops and domestic livestock, \( i = f \)) and game meat \( (i = g) \) using two factors \( (q_i \leq 0): \) land \( (i = t) \) and labor \( (i = l) \). The household possesses a production technology \( J(q;w) \) that relates factors and products, conditional on the weather and other environmental conditions \( (w) \) that are fully known to the household but may vary from year to year.\(^5\) The household has an endowment \( (e_i \geq 0) \) of each commodity. The household maximizes the utility it derives from the consumption \( (c_i) \) of traditional foods \( (i = f) \), game meat \( (i = g) \), nonfood household goods \( (i = h) \), and leisure \( (i = l) \), given household size \( (n) \), and subject to a cash budget constraint that includes both proceeds from its own activities and transfers from outside \( (s) \). Perfectly competitive markets exist for traditional foods and nonfood household goods, so the household buy and sells those products freely at a given price. These are hereafter referred to as tradable commodities (the set \( T = \{f, h\} \)). No markets exist for game meat, labor (leisure), or land; the household must fully self-provision in these factors and products.\(^6\) These commodities are thus labelled nontradables (the set \( NT = \{g, l, t\} \)).

Given these characteristics, the household solves the following problem:

\(^5\)For purposes of tractability, we employ a simple static model under certainty. An interesting extension would be a more general, stochastic dynamic formulation that recognizes intertemporal demand patterns and the effect of stochastic technology on consumption and production patterns.

\(^6\)One can perhaps best understand the absence of markets in this representative household model as capturing the autarkic nature of the village economy in these commodities. While there is clearly some trade in labor, land, and meat among households within Serengeti villages, there seems to be far less intervillage trade. Moreover, agricultural households in the region surely do not face perfectly elastic demand or supply schedules for these commodities, hence, the simplifying assumption of complete markets failure.
max \quad U(c; n) \quad \text{subject to} \quad \sum_{i \in T} p_i(q_i + e_i - c_i) + s \geq 0 \quad \text{tradables' cash budget constraint} \quad (7a)

q_i + e_i - c_i \geq 0 \quad \forall i \in NT \quad \text{nontradables' availability constraint} \quad (7b)

J(q; w) = 0 \quad \text{production technology constraint} \quad (7c)

The constraints (7b-7d) represent the production technologies and market conditions prevailing in the region, which are presumed static. The Lagrangean associated with this constrained optimization problem thus takes the form:

\[ \mathcal{L} = U(c; n) + \lambda \left[ \sum_{i \in T} p_i(q_i + e_i - c_i) + s \right] + \sum_{i \in NT} \mu_i(q_i + e_i - c_i) + \phi J(q; w) \quad (8) \]

Note that nontradables' prices are endogenous in this problem, with \( p_i^* = \mu_i/\lambda \quad \forall i \in NT \), while tradables' prices are exogenous by assumption, \( p_i^* = p_i \quad \forall i \in T \). Assuming an interior solution,\(^7\) the first-order necessary conditions for an optimum can be written as:

\[ U_i = \lambda p_i^* \quad \forall c_i \quad (9a) \]

\[ \phi J_i = -\lambda p_i^* \quad \forall q_i \quad (9b) \]

\[ \sum p_i c_i = \sum p_i (q_i + e_i) + s \quad i \in T \quad (9c) \]

\[ c_i = q_i + e_i \quad \forall i \in NT \quad (9d) \]

\[ J(q; w) = 0 \quad (9e) \]

Algebraic manipulation of equations (9) produces a generalized profit function,

\[ \pi^*(p^*, w) = \sum p_i^* q_i, \text{ a system of input demand and output supply equations, } q^* = q(p^*, w), \text{ a} \]

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\(^7\)Equivalently, assuming \( U() \) is strictly increasing in its arguments. This assumes that the income elasticity of demand for game meat is positive. While it is probably true that game meat becomes an inferior good as people become sufficiently wealthy (and substitute beef for game), for the context we examine, the current generation of a very poor population, this assumption is reasonably innocuous.
function defining full income, \( y^* = \pi^* + \Sigma p_i^* e_i + s \), and a system of demand equations, 
\[ c^* = c(p^*, y^*). \]

The key feature of this model of household behavior is that the price of game meat and the wage rate for labor are both endogenous, which induces households to reallocate their time between labor on the farm, poaching, and leisure. These endogenous prices are a function, in part, of agricultural productivity, which is subject to external shocks. In years with adverse production conditions, the marginal product of agricultural labor declines and the marginal opportunity cost of leisure increases, making poaching relatively more attractive. This feature of the model captures the propensity of peasants to poach as a survival strategy in the face of crop failure.

Endogenous prices and wages are also a function of endowments (including meat quotas received from SRCS) that partly or fully satisfy demand for game meat or leisure. Note that in order to prevent poaching completely, SRCS must provide game meat such that \( e_g = c_g \). This relaxes constraint (7c), reducing its associated multiplier, \( \mu_g \), thereby driving \( p_g^* \) (and the marginal returns to poaching) to zero. At the same time, \( y^* \) increases with \( e_g \), stimulating game meat consumption through both income and substitution effects. This basic point is too often overlooked in ICDP design. PAMs often recognize that carcass distribution from managed culls can reduce or eliminate poaching, but they typically fail to note that it simultaneously stimulates game meat consumption. This plants the seed of the mechanism’s destruction, which occurs faster the more income and price elastic is the demand for game meat. There may be sound biological reasons for managed harvests if these are less harmful to the species’ population.
dynamics than an identical volume of poaching. But managed harvests for distribution to human populations that would otherwise poach necessarily increase offtake volumes. Moreover, note that the $e_g$ necessary to induce peasants to quit poaching is endogenous, depending upon the realization of environmental shocks, $w$, to agricultural production. Even if the PAM can accurately elicit local households’ willingness to accept (WTA) value for poaching the first year—the $e_g$ value that yields $q_g = 0$ conditional on known $w$—that amount will change each successive year with probability one. Where game poaching and consumption behaviors are endogenous, the PAM must be prepared either to renegotiate the ICDP contract or to observe poaching virtually every period.

The effects are only slightly different if the PAM provides income transfers in another form, i.e., the ICDP contributes to $s$ rather than to $e_g$. Then the transfer again produces positive income effects on $c_g$, but now the substitution effects are negative because cash transfers reduce $\lambda$. The net effects on game meat consumption are ambiguous, but the returns to poaching are increased by raising the relative price ($p_g^*$) of game meat. The more fungible the asset transferred, the less will the effects of the transfer concentrate on game meat demand, but poaching could well increase. While the results of this model relate specifically to ICDPs based on game cropping, we see no reason to expect other sorts of transfers to yield qualitatively better results.

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8 Our model does not capture these prospective differences.

9 Note that this result follows automatically from the assumptions that game meat is (1) nontradable ($c_g = e_g + q_g$), and (2) a normal good ($\partial c_g / \partial e_g > 0$). Combine these and simple calculus and algebra reveals that $\partial q / \partial e_g > -1$, i.e., there is less than a one-for-one tradeoff of PAM-distributed meat for poached game.
We need to specify particular functional forms to operationalize this model. A parsimonious specification makes sense given the dearth of empirical information on the behavioral patterns of peasant agriculturalists in the Serengeti region. Like Barnum and Squire [2], we employ a Stone-Geary utility function to economize on parameters and to explicitly incorporate subsistence needs. The specific model for (7a) is thus:

\[
U(c,n) - \gamma \Pi_j \left( \frac{c_j - k_j}{n} \right)^{\theta_j}
\]

for \( j = f, g, h, l \) (10)

where \( \gamma \) and the \( k_j \)'s are positive constants, with the \( k_j \)'s representing subsistence minima. We set \( k_f \) at \( \frac{1}{2} \) kg/household per day of maize, the staple food in the region, \( k_h \) — representing medicines, cooking fuel, building materials, tools, etc. — at 40% the expenditure level of \( k_f \), \( k_l \) at 5% of household labor time, and \( k_g = 0 \). Without loss of generality, let \( \sum_j \theta_j = 1 \) and \( \theta_j \geq 0 \forall j \). Based on household expenditure data [22], we set \( \theta_f = 0.5 \), \( \theta_g = 0.15 \), and \( \theta_h = 0.3 \).

Similar concerns for parsimony motivate a Cobb-Douglas specification of technologies:

\[
q_g = b_g(-q_{lf})^{\gamma_f} \quad q_l = b_l(-q_{lg})^{\gamma_f}(-q_{lf})^{\gamma_g} e^w
\]

\( w = z \cdot d_v + z \cdot \frac{\rho \Omega}{(1 - \rho) \xi} \) (12)

where \( q_l = q_{lf} + q_{lg} \), \( z \) is an \( N(0, \Omega) \) exogenous shock to agricultural yields that is independent from \( v \), the \( N(0, \xi) \) rainfall shock from section IIa, and \( \rho \) is the correlation coefficient between these shocks. Simulations in section III proceed on the assumption that \( v \) and \( z \) are serially independent and identically distributed. We set \( \Omega \) so as to maintain a constant variance of \( q_{lf} \), equal to observed variability in yields for maize, the dominant crop in the region, over the past twenty years [20]. Since it is unclear how poaching yields vary with rainfall, \( q_{lg} \) is modeled as a deterministic function of \( q_{lg} \). We assume decreasing returns to labor in both agriculture and
poaching as well as constant returns to scale in agricultural production \((0 < \gamma_i < 1\) for \(i = 1, 2, 3,\) and \(\gamma_2 + \gamma_3 = 1\)), with \(\gamma_1 = 0.9\) and \(\gamma_2 = 0.8\). The production function constants, \(b_f\) and \(b_g\), were set at 10 and 1, respectively, so as to calibrate local maize output and game offtake volumes at \(w = 0\) to the best estimates of current levels. Finally, mean land per rural Tanzanian household is 4.7 hectares [20], so \(e_t = -q_{it} = 4.7\).

Average household size in the Serengeti region was \(n = 7.03\) persons in 1988 [6]. Using a conservative estimate of 1.25 million persons in proximity to the park in 1995, we use a base of \(hh_0 = 177,800\) households. Let \(l = n\), i.e., all household members are available to work. We assume that human populations in the Serengeti continue to grow at the long-term rate, based on 1957-88 census data, of 2.9% per year [16], with growth arising through increased numbers of households, i.e., \(hh_{t+1} = 1.029hh_t\).

Section IIa deferred definition of the harvest volume, \(H_t\), to this section. Let us now define gross game meat demand as \(D_t = c_{gt} \cdot hh_t = (e_{gt} + q_{gt})hh_t\). Data on animals killed by poachers indicates that wildebeest comprise about 60% of poaching volumes, by either number or metabolic weight, making them by far the largest target species in the Serengeti [1]. We thus assume a constant 60% proportion of poaching \((q_g)\), game meat consumption \((c_g)\), and SRCS meat distribution \((e_g)\) are wildebeest. Our decision rule is thus that as long as \(0.6D_t \leq H_t^*\), i.e., as long as human demand does not threaten the sustainability of the wildebeest herd, then the PAM will honor the quasi-contract and deliver \(0.6e_{gt}\), so that \(0.6D_t = H_t\). The biologically, politically, and socially perilous point we define as crisis arrives, however, when \(0.6D_t > H_t^*\). The next section presents simulations of how long until the PAM faces crisis in managing the ICDP.
III. Simulations of Time to Crisis

We generated an empirical distribution of the time to crisis by replicated simulations of the model in section II. In each period of each simulation, we randomly drew with replacement the three exogenous variables \((u, v, z)\) from their specified distributions and the \(\alpha, \beta\) parameters from PH's [13] published joint distribution. Based on these realizations of the time-varying exogenous variables, we solve the household's constrained optimization problem, computed the wildebeest population size, and determined whether \(0.6 D_t > H_t^*\). If not, we let \(N\) and \(hh\) grow according to the laws of motion specified in section II, then began the next period by resampling \(u, v, z, \alpha, \beta\). Each simulation was replicated 300 times. We repeated this process 27 times, to account for alternative assumptions about: (1) the correlation between shocks to rainfall and to agricultural productivity \((\rho)\), (2) the contractual volume of wildebeest meat given each household by the PAM \((e_g)\), and (3) the endogenous rate of human population growth \((m)\). Table 1 reports the median and standard deviation of these empirical distributions, as measured in years.\(^{10}\)

In each of the 27 scenarios, the median simulated time to crisis is fairly short, between 9 and 14 years. Among the 8,100 simulations, the minimum time to crisis was 2 years, the maximum 58. Note also the relatively small standard deviations in Table 1, which range only between 2.9 and 4.1 years. If our parameterization of household behaviors is anywhere near accurate, there seems strong reason to suspect that ICDPs with a substantial game cropping component are likely to collapse in 6-18 years.

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\(^{10}\)Any simulation makes a multitude of assumptions which are impossible to validate. Still, it is good practice to ensure that one’s model would not predict a history other than that which has been observed. Toward this end we simulated this model 20 times from a 1980 base. None of these simulations yielded collapse prior to 1995, so it does not seem our parameterization strongly biases simulation results in favor of early collapse.
The concentrated period of likely ICDP collapse is highlighted graphically in Figure 1, which portrays the effects of the sensitivity analysis performed with respect to $e_g$, $m$, and $p$. In our best case scenario, corresponding to the upper leftmost cell in Table 1a ($e_g = 0.33$, $m = 0$, $p = 0.3$), the PAM has a 0.5 probability of facing crisis within 14 years and a 0.1 probability of facing crisis within 10 years. An intermediate scenario, the central cell from Table 1b ($e_g = 0.5$, $m = 0.005$, $p = 0.5$) shows a cumulative frequency distribution lying entirely to the left of the best case scenario distribution, with a 10% chance of crisis within 6 years and a 50% chance of crisis within 10 years. The most alarming situation follows from our worst case scenario, corresponding to the lower rightmost cell in Table 1c ($e_g = 1.0$, $m = 0.01$, $p = 0.7$). If these parameters are accurate, then the 0.1 and 0.5 probability levels for time to crisis are at only 5 and 8 years, respectively.

Note from Table 1 that the median time to crisis changes quite symmetrically as one varies any of the three parameter values ($e_g$, $m$, or $p$). These may be merely modeling artifacts, and, without strong empirical underpinnings to the human behavioral model, we cannot say much about the relative magnitudes of these effects. Nonetheless, we believe this reflects primarily initial proximity to the biologically maximal harvests predicted by PH. Almost any increase in total offtake, no matter the reason, thus leads to collapse in a short number of years.

One can see this most clearly by looking at a plot of a representative simulation. Figure 2 displays the time path of both human demand, $H_t$, and the maximum noncatastrophic harvest, $H_t^*$, for one base case simulation ($e_g = 0.33$, $m = 0$, $p = 0.3$) that yielded crisis at the median time of 14 years. Plotted along with those time series is the weighted least squares regression line of
$H_t$ on time, representing the linear time trend in human game meat demand. Notice that crisis occurs when the wildebeest population suffers a severe negative shock, bringing the herd size down to the region where secular growth in or a shock to human demand for game meat can induce crisis.

Consider Figures 3a, 3b, and 3c, which overlay the fitted values of $H_t$ under alternative parameter value assumptions. In Figure 3a, we compare the base case with a scenario of high game meat distribution ($e_g = 1.00$, $m = 0$, and $\rho = 0.3$), increasing the intercept to account for a greater initial income effect on game meat demand and, thereby, shifting the whole regression line upwards, leading to earlier crises. Positive endogenous effects on human population growth change not the intercept of the regression line, but its slope does change. Thus, in Figure 3b, with $m = 0.01$ (and $e_g = 0.33$, and $\rho = 0.3$), more rapid human population growth induces steeper increases in game meat demand and earlier crises than under the base case. Finally, an increase in the correlation of environmental shocks affects not the intercept or slope of the regression line so much as the variability of the estimator. Thus, in Figure 3c, when we let $\rho = 0.7$ (with $e_g = 0.33$ and $m = 0$), there is very little change in the regression line from the base case, but the 90% confidence band around the regression line widens noticeably. This reflects the higher probability of a common environmental shock causing human demand to increase and intersect earlier with the maximum noncatastrophic wildebeest harvest. The three parameters we vary in the simulations thus impact in different ways on human demand for game meat, but the end results, as

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11 These are the fitted values from the weighted least squares regression, $w_t^{\hat{H}_t} = w_t^{\hat{H}_t} + e_t$, where the $w_t$ are the inverse of the cumulative frequencies depicted in Figure 1 and the $e_t$ are iid normal residuals. These regressions were estimated on the 300 replicates generated for the relevant simulation (in this case with $e_g = 0.33$, $m = 0.00$ and $\rho = 0.3$).
depicted in Table 1, are strikingly similar. Variation in any one of the parameters brings human demand into a threatening range earlier than under the base case.

IIIa. Alternative Environmental Stochasticity Correlations

PH's simulations using the model of section IIa suggest that the probability of population collapse increases exponentially with annual harvest volume, exceeding 20% (over a 200-year timeframe) once total harvest reaches 50,000 or more wildebeest, a figure well below estimated current offtake levels. They note that constant harvest rate regimes produce far lower probability of herd collapse than constant harvest volume regimes producing the same average catch. PH find that the expected harvest increases rapidly with higher rainfall because of a higher recruitment rate in the herd.

Like most existing studies of harvest or poaching patterns, PH ignore human demand patterns. Once one accommodates endogenous human poaching and meat consumption, the positive relationship between harvest and rainfall may break down, rendering constant harvest rate regimes socially infeasible. This is because poaching is an important form of income insurance in the event of crop failure. The stronger the correlation between rainfall and agricultural productivity, the more amazing is the "insurance" activity of poaching because covariate shocks to the wildebeest herd and crop yields induce greater human dependence on wildlife just as the herd can least withstand increased harvest.

The adverse effect of covariate environmental stochasticity on ICDPs' durability is reflected in Table 1. Holding $e_g$ and $m$ constant (i.e., reading down the columns in each of the three panels in Table 1), median time to crisis consistently declines as $\rho$ increases. Because
poaching becomes relatively attractive when external shocks (e.g., drought) depress labor productivity, covariate shocks that depress both food availability for wildebeest and agricultural labor productivity will almost inevitably increase harvest rates. A constant harvest rate strategy is likely futile in such a setting, because it is unlikely to satisfy local game meat demand and so will not have its intended effect of curtailing illegal hunting.

The positive relationship between the relative returns to poaching and the correlation of environmental shocks and agricultural yields highlights the importance, from a conservation biology perspective, of agricultural research and extension to improve drought resistance among crops and animal epidemiological control among livestock. Agricultural development specialists and conservation biologists concerned about environments like the Serengeti have shared objectives in this area.

IIIb. Alternative Managed Harvest Meat Distribution Volumes

We set the baseline value for $e_g$ to $\frac{1}{3}$ wildebeest per household per year, i.e., the current estimated consumption/poaching volume, and in the range of original legal harvest plans, which are presently not being met due to donor funding cuts. This is shown in the first column of each of the three panels in Table 1. Given the broad range of estimates for game meat consumption volumes, it could be argued that a higher distribution rate of $\frac{1}{2}$ to 1 wildebeest/household per year may be necessary to curtail poaching. We simulate the model under each of these scenarios.

A higher offtake volume, $e_g$, does diminish poaching rates, although poaching remains common given a static distribution volume (i.e., no renegotiation of contractual compensation under the ICDP). The percentage of periods in which $q_g = 0$ was 11.1% with $e_g = 0.33$, almost all
in the initial periods of the simulations. This figure increased to 17.3% when $e_g = 0.5$ and to 28.8% when $e_g = 1.0$. Notice there is a positive level of poaching activity most periods, because the transfer level is constant over time while demand for game meat and the relative returns to alternative activities change over time. This illustrates the point made in section IIb, that the $e_g$ necessary to induce peasants to stop poaching is endogenous and thus variable over time.

While a higher distribution rate, $e_g$, discourages poaching, it simultaneously stimulates game meat consumption due to income and substitution effects, thereby hastening the time to crisis in ICDPs. Holding $m$ and $\rho$ constant (i.e., reading across the rows in each of the three panels of Table 1), median time to crisis consistently falls as $e_g$ rises. The qualitative effects of increasing game meat distributions are thus the same as those from increased correlation of environmental stochasticity between wildebeest survival and recruitment rates and agricultural production, as highlighted earlier. The important difference is that while the PAM has only limited, long-term, indirect influence over $\rho$ (through support for agricultural research and extension in the area), s/he has direct control over $e_g$. Our results suggest smaller distributions of game meat help preserve the herd, even though they might not reduce poaching.

IIIc. Endogenous Human Population Growth Rates

Up to this point we have assumed the introduction of an ICDP providing income transfers to the local population has no effect on the rate of human population growth. This is a conservative assumption. Population growth rates in the Serengeti region are historically somewhat lower than in the rest of Tanzania (and in neighboring Kenya). We suspect this is largely attributable to greater rates of out-migration, lower rates of in-migration, and higher
mortality rates owing to the region’s relatively more widespread and severe poverty. Amelioration of such differences and improved nutrition from more reliable availability of calorie and protein sources such as game meat would likely increase the human population growth rate in the reasonably near-term which we study.\textsuperscript{12} We now generalize the earlier formulation of growth to

\[ hh_{t+1} = (1.029 + m)hh_t, \]

where \( m \) is the endogenous component of the local human population growth rate. The baseline simulations discussed in section II and presented in Table 1a implicitly set \( m = 0 \). We resimulated the model under two less conservative estimates, \( m = 0.005 \) and \( m = 0.01 \), corresponding to local human population growth rates of 3.4\% and 3.9\%, respectively.

It should be obvious that the greater the human population base drawing on the wildebeest herd for food and income, the larger the harvests. Thus, more rapid human population growth inevitably leads to greater pressure on the ecosystem and earlier collapse of the ICDP. This can be seen in the declining median time to crisis as \( m \) increases, holding \( e_g \) and \( p \) constant (i.e., as one looks down the three panels in Table 1). Of course, we have modeled all population growth as coming in the form of new households. These effects might be muted somewhat if a large part of human population growth came instead from expanding average household size, although the limited available evidence suggests that most population growth in the region in the past generation has come from increased numbers of households rather than more people in households [6, 22].

\textsuperscript{12}Long-term declines in human fertility rates associated with improved standards of living far exceed the time horizons of interest here.
IV. Discussion

We have relied heavily on PH’s [13] model of wildebeest population dynamics. PH estimate the probability of population collapse under different harvest regimes, implicitly assuming human demand and poaching patterns are completely controllable by protected area managers. We extend PH’s work by explicitly modeling endogenous human behavior, following the nonseparable agricultural household modeling technique introduced by DeJanvry et al. [7]. In particular, we study how long ICDPs might reasonably be expected to serve as a palliative in the longer term struggle to refocus attention and resources on parallel processes of rural development, poverty alleviation and wildlife conservation.

Our model enormously simplifies the interaction within the Serengeti ecosystem of wildebeest population dynamics with patterns of human demand for and poaching of game meat, each of which is likely to be complex in its own right. Yet this model captures some key features of this poorly understood interaction. Wildlife poaching is a source of food and income for extremely poor human populations subject to considerable risk of nutritional catastrophe. Although we emphasize that our parameterization of human demand patterns are merely guesses—and that the vacuum of careful social science research on the etiology of human impacts on wildlife populations must be made a research priority—our simulations suggest that African wildlife ICDPs, with a significant game cropping component, are unlikely to survive long in their present design.

Note that we have used optimistic assumptions in this simulation: e.g., that wildebeest harvests do not exceed historical proportions (60%) of poaching or game meat demand, that the
human population base for game meat demand is purely local\(^{13}\) and that there will be no recurrence of prolonged dry season drought like that experienced in the Serengeti in the 1960s. Our sense is thus that the simulation results presented above are as likely to overstate as to understate the risk of near-term collapse for African wildlife ICDPs that are substantially dependent on transfers to the local population.

As the discussion in section IIb emphasized, the seemingly static nature of agricultural production technologies and market conditions in the face of growing human populations are the crux of the threat to protected species. Poaching levels are a function of the maximum alternative returns to a peasant's labor and on household income. African farmers respond rationally to climatic or epidemiological shocks that depress the productivity of farm work [8]. When there are few, if any, alternative sources of food and income, locals rationally prey on protected wildlife species. Given that the wildebeest population varies directly with rainfall, the more covariate the environmental shocks to wildlife populations and agricultural yields, the greater the poaching pressure on the herd at precisely the moment it can least ably sustain added harvest. We suggest, therefore, that obviating such pressures must be a high priority in conservation strategies. Obvious but challenging avenues for doing so include agricultural research that improves pest control and drought resistance for crops and epidemiological control for domestic livestock, and the activation of rural labor markets that might provide a competitive wage floor on the returns to

\(^{13}\)There have long been unconfirmed reports that poached game meat is trucked out of the area to urban centers like Kisumu, Musoma, Mwanza, and even Nairobi. If this is true, then the consumer population is much larger, perhaps by an order of magnitude. If communications and transportation infrastructure development in the area continues, the effective market for game meat will surely grow rapidly. Note that a far larger spatial market would also invalidate the assumed nontradability of game meat, which would tend to exacerbate the problem of poaching in response to crop failure, since game meat sales could be used to finance traditional food purchases, thus, stimulating even more poaching than occurs in our model.
labor time, thereby rendering poaching an inferior activity. Reducing the returns or increasing the risks to poaching through fortified enforcement efforts, as SRCS plans to do, likewise discourages peasant reallocation of labor time to poaching, although it fails to decouple rural livelihoods from poaching. Covariate environmental risks inevitably pit PAMs against local populations as long as wages are endogenous.

Growth in human demand for game meat, attributable to both income and human population growth, poses a long-run threat to the wildebeest and other wildlife populations slated for harvest as part of an ICDP. Insofar as ICDPs provide an income transfer to locals and, thus, induce in-migration, they may further hasten their own collapse. Moreover, as communications and transport improve in the region, reducing marketing costs and expanding the spatial market for wildlife products, game meat will from the nontradable good category modelled here to the set of tradables. Then meat distribution from managed harvests will cease to reduce the returns to poaching. Game cropping will still become a less effective means to reduce poaching, and each may continue to stimulate game meat consumption.

Finally, it is important to note that in principle ICDPs are supposed to foster cooperative efforts between parks staff and local populations and that observed instances of success in ICDPs so far correlate closely with strong cooperation among all parties to the quasi-contracts [5, 21]. Our model, however, is one of myopic, self-interested behavior that ignores the possibility of cooperative action. However, we do not mean to imply that the human communities around the

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14Bluffstone [4] analogously finds that a competitive labor market offering a known, even if low, off-farm wage rate can obviate deforestation problems even under open access.

15Our model assumes constant enforcement effort and certain returns to poaching. A useful extension would generalize these characteristics.
Serengeti or other large reserves are incapable of cooperation and self-policing. Instead, our concern is that cooperative strategies may not be viable given the region's severe poverty and the imperfect abilities of authorities to monitor illegal harvests. For example how do village leaders ensure that young men suffering poverty-induced undernutrition do not set line snares to poach migratory ungulates while they tend livestock out of view of the village? This is a serious challenge in the design of enforceable contracts between parks officials, community leaders, and community members.
References


Table 1: Simulation Descriptive Statistics

Table 1a: Human Population Growth = 2.9% (m = 0)

<table>
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<td>$\rho = 0.5$</td>
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<td>11 (3.5)</td>
<td>10 (3.5)</td>
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<tr>
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<td>10 (4.1)</td>
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Table 1b: Human Population Growth = 3.4% (m = 0.005)

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Table 1c: Human Population Growth = 3.9% (m = 0.01)

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<tbody>
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<td>9 (3.2)</td>
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</table>
Figure 1. Graphical depiction of time to crisis distributions
Maximum noncatastrophic harvest

Human harvest demand

Figure 2. Sample time paths for $H_t$ and $H^*_t$
Figure 3a. Fitted harvest volumes with $e_g = 1.0$
Figure 3b. Fitted harvest volumes with $m=0.01$
Figure 3c. Fitted harvest volumes with $\rho=0.7$