The Economics of Protecting Tiger Populations: Linking Household Behavior to Poaching and Prey Depletion

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ABSTRACT. *The tiger* (Panthera tigris) *is classified as endangered and populations continue to decline. This paper presents a formal economic analysis of the two most imminent threats to the survival of wild tigers: poaching tigers and hunting their prey. A model is developed to examine interactions between tigers and farm households living in and around tiger habitats. The analysis extends the existing literature on tiger demography, incorporating predator-prey interactions and exploring the sensitivity of tiger populations to key economic parameters. The analysis aims to contribute to policy debates on how best to protect one of the world's most endangered wild cats.* (JEL Q22)

I. INTRODUCTION

The earth's remaining wild tiger (*Panthera tigris*) populations continue to shrink and fragment under ever increasing human-related pressures. Over time, human activities have reduced tiger habitats by more than 90%. As a consequence, tigers now live in only a small fraction of the potential habitat. Recent estimates suggest that wild tigers inhabit less than 5% of the 1.5 million km² of forest habitat available (Karanth 2001). At present, more tigers exist in captivity than in the wild (Nowell and Jackson 1996).

The evidence to date indicates that wild tiger populations continue to decline despite substantial conservation efforts by international agencies, local conservation groups and governments (Seidensticker, Christie, and Jackson 1999). The IUCN identifies tigers in all the range countries as endangered and the signatories to CITES have placed a ban on all international trade in live tigers and tiger parts.

Tigers need extensive areas to hunt and breed, thus protecting wild populations and sustaining their habitats present wildlife managers with a set of complex and daunting tasks. For instance, tigers are large-bodied, obligate carnivores and readily come into conflict with humans by killing livestock, and occasionally people. Tiger numbers are sensitive to the depletion of their prey caused by local hunting (Karanth and Stith 1999). The role tigers play as top predators is vital to regulating and perpetuating ecological processes and systems (Sunquist, Karanth, and Sunquist 1999; Terborgh 1999). If either predator or prey numbers decline, entire ecological communities may become unstable with more and more species being gradually lost.

A further difficulty for conservation efforts is that wild tigers occur only in Asia, where the high incidence of rural poverty, large numbers of livestock and high levels of human population density and growth speed forest degradation. Unlike much of Africa and Latin America, the vast majority of for-

ests in Asia have already been converted to other land uses. In countries like India, forest boundaries appear to have stabilized and the major conservation management problem is most often related to how communities use forest resources within protected areas and public forests (Wells 1992; Ghimire 1994; Nepal and Weber 1995; Studsrod and Wegge 1995; Gunatilake 1998; Gunatilake and Chakravorty 2000; Kumar et al. 2000; Lele et al. 2000).

The proximate causes for the persistent decline of wild tiger populations are many. Pressures vary regionally and change over time. The numerous forces threatening the tiger's survival include poaching, prey depletion and habitat fragmentation due to land clearing, livestock grazing, weed infestations, fuelwood and fodder extraction, smuggling for the illegal timber trade, and intrusive infrastructure (World Bank 1996; Siedensticker, Christie, and Jackson 1999). What the relative contributions of these forces are to declining tiger populations and how they interact are less well understood. Tiger poaching, which is driven by the demand for tiger products in the traditional Oriental medicine trade, and prey depletion caused by local hunting are considered to be the most imminent threats to survival of the species in the short run. In the early 1990s, wildlife authorities observed a dramatic escalation in the scale of poaching as tigers were killed to satisfy the burgeoning demand for tiger bones and organs for traditional Oriental medicine (Meacham 1997).

The demographic consequences of declining tiger populations through poaching and prey depletion have been examined in previous research (Kenney et al. 1995; Karanth and Stith 1999). However, no formal studies have examined the fundamental economic causes driving wild tigers to extinction. This paper argues that a clearer understanding of how biological factors interact with economic forces is crucial for guiding policy choices aimed at sustaining viable habitats and reversing the decline in wild tiger populations. The work presented here represents a first attempt to integrate economic incentives into a predator-prey model of tiger ecology.

The paper is organized as follows. Section 2 provides a brief description of the background to the problem. Section 3 outlines the basic model, describing the behavior of subsistence farmers and their interaction with tigers and their prey. Section 4 presents a stage-based demographic model of tiger population growth dynamics. Section 5 outlines the simulation results of alternative scenarios. Section 6 concludes the paper.

II. BACKGROUND

The tiger once had a wide distribution stretching across Asia from Bali, through India, to the Russian Far East, and West Asia. Hunting and habitat erosion have exterminated tigers through much of their previous range. Most reserves are isolated from each other and contain less than 30 animals (Siedensticker, Christie, and Jackson 1999). Tigers feed predominately on large ungulates (hoofed mammals such as deer, pigs, and wild cattle). They cannot survive if a habitat does not support sufficient densities of large ungulates. To meet its basic nutritional needs, an average tiger requires a minimum of 3,000 kg of meat (or about 50 ungulates) per annum to survive (Sunquist, Karanth, and Sunquist 1999). A tigress raising three cubs may need twice that amount. Like other big cats, tigers can crop only 10% of the available prey biomass, suggesting that approximately 500 ungulates are required to support one tiger in the wild (Karanth 2001).

Tigers require vast forest areas of reasonable quality in which to roam, hunt, and breed. Tiger densities vary across regions. In relatively prey-rich forests, such as India's Kanha, Kaziranga, and Nagarahole National Parks, densities can exceed 10–15 tigers per 100 km^2 (Karanth and Nichols 1998). In contrast, in areas where prey is less abundant and more widely dispersed, like the Russian Far East, tiger densities are considerably lower; less than 1–2 tigers per 100 km^2. The central message emerging from the biological studies is that where prey is plentiful, tigers survive and may even endure limited poaching pressures.

Conserving wild tiger populations requires protecting the quality of their habitat

as well as their prey base. The forests that tigers and their prey inhabit provide a wide range of economic, social, and environmental benefits to people. These benefits contribute greatly to human welfare, but they are valued differently by different people and different groups. Local, national, and international interests in tigers and their habitats also differ greatly across landscapes. To government policymakers, tiger habitats are often seen only for their ability to generate income, employment, revenue, and foreign exchange when converted to agriculture, timber, mines or other development-oriented activities. To a small proportion of the humans living in and around the forests, killing tigers for their body parts yields a substantially greater income than live tigers roaming free. Many small-scale agricultural producers view tigers and their prey as pests that damage their livestock and crops.

Various studies document the crop damage caused by large ungulates (Sekhar 1988; World Bank 1996). Little quantitative information is available about two of the most imminent threats to the survival of wild tigers: the poaching of tigers and poaching of their prey. Recent investigations suggest that the trade in tiger parts is controlled by organized criminal groups, involved in a host of other illegal activities. In contrast, tiger poaching is undertaken by locals who have an intimate knowledge of the forests. The evidence suggests that the illegal traders capture the bulk of the profits, while poachers are paid low prices for each tiger killed (Nowell 2000; WPSI, 2001).[1]

National governments tend to influence control over the choice of forest benefits. When traditional rights and access shift in ways that adversely impact local communities, households may have little incentive to use natural resources, and in particular protect animals, in a sustainable way (Barbier 1992; Panayotou 1993; Gunatilake 1994, 1998; Tisdell 1995; Shyamsundar and Kramer 1996). For this reason, providing greater access and use of tiger habitats is often argued as the appropriate response to meet conservation objectives (Saberwal 1996; Kothari, Suri, and Singh 1995).

India possesses the largest number of wild tigers of any of the range states and has had a relatively successful history of tiger protection (Nowell and Jackson 1996; Karanth 2001). Its response to declining tiger populations focuses on establishing special protected reserves and on law enforcement.[2] Although the appropriateness of policy measures needed to halt or reverse declining tiger populations is still contested, the overall management approach has recently shifted towards a participatory style known as Joint Forest Management (JFM), at times driven by external donor encouragement. The extent to which JFM is adopted varies by state in India. In most cases, households living in or near forests utilize timber and non timber forests resources for subsistence, cash and wage incomes (d'Silva and Nagnath 2002). Through sharing products, responsibilities, and decision-making authority, JFM approaches seek to provide local communities with incentives to protect the forest resources that provide their income base and future welfare.

Some argue that JFM should also be extended to reserves aimed at protecting wildlife (Kothari, Suri, and Singh 1995). Other studies raise important concerns about the appropriateness of JFM-style conservation and protection efforts (Gunatilake 1998; Karanth and Stith 1999). For instance, Barrett and Arcese (1995, 1998) question the assumptions linking local communities and sustainable forest resource use across diverse geographic conditions and economic situations. Simpson (1995) suggests the need for greater experimentation with direct-payment for conservation efforts, rather than funding untested participatory projects based on raising the value of forest products in ways that may fail to deliver improved conservation outcomes. This view finds support in Gunatilake's (1998) analysis of Sri Lanka which provides evidence that policies aimed at reducing dependency on forest based resources

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[1] For instance, Nowell's (2000) study of the trade in tiger parts suggests that the retail value of an adult male tiger varies from $15,000–$20,000, while the Wildlife Protection Society of India reports cases where poachers in the field are paid $15–$20.

[2] The Indian Government introduced the Project Tiger program in 1973.

can be a much more effective way to protect forests than policies aimed at using forest resources. The issues concerning participatory management addressed in these studies raise important questions about the appropriateness of the widespread promotion of JFM in India for protecting tigers.

The model and simulations presented here examine how the tiger's biological needs interact with economics incentives facing households living in and around their habitats. The analysis aims to contribute to the policy debate about how best to protect tiger populations.

III. THE MODEL

Most of India's tiger habitats are in parks and protected areas that also support various forms of land uses, including agriculture, livestock grazing and fuelwood collection (Mishra 1997; Sekhar 1998). The interspersion of humans in and around these parks leads inevitably to conflicts over resource use (Schultz and Skonhoft 1996). Two motives for local people hunting the tiger's prey species are considered. The first is when the large ungulates cause damage to crops in adjoining agricultural areas, termed the ''nuisance effect'' by Marks (1984). The second motive arises from the incentive of subsistence producers to hunt ungulates as a supplementary food source. On the other hand, the incentive to hunt tigers is driven entirely by the demand for tiger products.

The context for this model is a wild tiger population in an insular forest patch surrounded by agricultural land—a typical characteristic of tiger reserves on the Indian subcontinent. We extend the most recent model of tiger population dynamics developed by Karanth and Stith (1999), to include predator-prey interactions. The biological model is incorporated into a household production model in which subsistence farmers hunt tigers and their prey.

The model presented here is similar to Bluffstone's (1995) analysis of fuelwood extraction by subsistence farmers in Nepal. It is more closely related to Barrett and Arcese's (1998) model of the hunting incentives for farmers in an integrated conservation and de-

velopment project (ICDP) in Tanzania.[3] This paper extends this literature by incorporating an economic model of poaching behavior into a multiple species, predator-prey model.

The Household Model

As noted earlier, we consider a tiger reserve that is surrounded by agricultural land. The production and consumption units are households engaged in four kinds of activities: agricultural production, off-farm work, hunting tigers and hunting herbivores (i.e., the tiger's prey). Income from agricultural production and off-farm work is used to purchase food and other commodities. Households hunt prey animals as a supplementary source of food and to protect crops from damage.[4] The incentive to poach tigers is driven entirely by the illegal trade in tiger products that is controlled by criminal gangs who determine the price paid to farmers for each tiger killed.[5] Since very little is known about the nature of such poaching, we adopt functional forms with parsimonious data requirements. There are N households in the area surrounding the tiger reserve. A Cobb-Douglas function is employed to represent household utility:

$$U = \alpha_F \log(F) + \alpha_z \log(Z) + \alpha_x \log(h_x) \qquad [1a]$$

where: F represents consumption of food, Z consumption of non-food items, h_x consumption of prey animals, $\alpha_i > 0$ ($i = F, Z, x$) are the parameters of the utility function, with $\alpha_F + \alpha_Z + \alpha_x = 1$.

Equation [1a] is maximized subject to the constraints:

$$wL_o + p_g G + (P_T - \theta_T \Omega_T) h_T$$
$$= p_z Z + p_F F + \theta_x \Omega_x h_x, \quad [1b]$$

$$G = k L_g^\beta (1 - \mu X), \quad [1c]$$

$$h_x = \delta L_x X, \quad [1d]$$

$$h_T = L_T^\gamma \left(\frac{T}{R}\right)^\varepsilon, \quad [1e]$$

$$L = L_o + L_g + L_x + L_T, \quad [1f]$$

where G is agricultural output, X is the biomass of prey animals, L_g, is labor time devoted to agriculture, L_o is labor time devoted to off-farm work, L_x is labor time spent hunting prey animals, L_T is labor time on hunting tigers and p_g, p_F, p_z, P_T are the prices of agricultural produce, food, non-food commodities and tigers respectively, $\theta_i (i = T, X)$ is the probability of being convicted for poaching tigers (T) and their prey (X) and $\Omega_i (i = T, X)$ is the fine per unit harvest if convicted for poaching tigers or their prey. T is the number of tigers and R the area of the reserve. $k, \xi, \beta, \gamma, \mu, \delta > 0$ are parameters.

By equation [1a] household utility depends on the consumption of food (F), other goods, (a non-food composite commodity [Z]) and the quantity of prey animals consumed (h_x).

Equation [1b] is the household budget constraint. Food and other goods are purchased at given prices p_z and p_F respectively. These purchases are financed by: (i) the sale of agricultural produce (G) which is sold at a price p_g; (ii) off farm labor (L_o) which is remunerated at a wage rate of w; and (iii) tiger poaching (h_T). The farmers receive an amount P_T, for each tiger killed, which is determined by traders. Since poaching is illegal, it may result in conviction. The expected

penalty for poaching tigers is $\theta_T \Omega_T$, where θ_T is the probability of detection and conviction, Ω_T is the fine per tiger killed. Thus the expected payoffs from tiger poaching is defined by: $p_T = (P_T - \theta_T \Omega_T)$. Finally, since poaching prey is also illegal, the household may incur an expected penalty, $\theta_x \Omega_x h_x$; where θ_x is the probability of detection and conviction, Ω_x is the fine per prey animal poached (h_x).

Equation [1c] describes the agricultural production function. Following empirical studies on subsistence farming in India, agricultural production (G) is assumed to depend upon labor inputs (L_g), where β is the elasticity and k a constant (Deninger and Biswanger 1998; Saha 1994).[6] The production function also takes into account the damage to crops by the grazing and trampling of wild tiger prey. This is given by (μX, where X is the biomass of prey animals and μ is the damage coefficient.

Equation [1d] describes the prey harvest production function. In the absence of data on poaching of ungulate-prey in tiger habitats, we adopt a functional form that has been used in African studies of ungulate hunting (Kinyua, van Kooten, and Bulte 2000). Thus, the harvest of herbivores (h_x) is a function of labor inputs (L_x) and the population of ungulate prey (X), with unit elasticities with respect to labor inputs and prey populations.

Equation [1e] is the tiger poaching production function. There is no data available on the nature of tiger poaching. Hence, any functional form that is adopted is necessarily conjectural. Existing evidence suggests that tigers are usually killed by poisoning, shooting, or setting traps and snares (WPSI 2001), techniques requiring only minimal investment in capital equipment. To economize on parameters, we abstract from the need for capital equipment and assume that the harvest rate depends on the density of tigers and

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[6] The models used by Deninger and Biswanger (1999) and by Saha (1994) focus on agricultural households. While it is unclear how appropriate their models fit the type of agriculture practiced in and around tiger habitats in India, the lack of better data limits our options.

the amount of search effort.[7] Tiger poaching is thus specified using a Cobb-Douglas function with search effort and tiger densities as the only arguments in the production function. The method by which the parameters on search effort (L_T) and tiger density (T/R) are estimated is described in the Data Appendix.

Equation [1f] is the time allocation constraint which requires that labor time devoted to off-farm work (L_o), agriculture (L_g), and hunting tigers and their prey (L_T, L_x) must equal the fixed endowment of time (L) available to the household. Leisure is not included as a choice variable as existing household survey data in potential tiger habitats in Nepal suggest that opportunities for leisure consumption are limited in such poor rural households (Bluffstone 1995).[8]

The utility maximization problem is based on the notion that households take the time path of exogenous variables, such as the stock of herbivores (X), as given. This reflects the fact that there are assumed to be many such households who have no property rights in wild animals. Hence, they have little incentive to take account of the future consequences of their current actions. Formally, this implies that households solve a static optimisation problem. Thus, for notational brevity, time symbols are suppressed in the above equations.[9]

Of particular interest in this context are the solutions for poaching tigers and prey animals. Solving the utility maximisation problem in equations [1a]–[1f], yields the following solution for the allocation of effort expended on hunting tigers in each household:

$$L_T = \left(\frac{\gamma p_T D^\varepsilon}{w}\right)^{1/(1-\gamma)}, \qquad [2a]$$

where $p_T = (P_T - \theta_T \Omega_T)$ is the net expected payoff from poaching a tiger, $D = T/R$ is the density of tigers.

Using [1e] the aggregate harvest of tigers is given by:

$$H_T \equiv Nh_T = N\left(\frac{\gamma p_T D^\varepsilon}{w}\right)^{\gamma/1-\gamma}(D)^\varepsilon. \qquad [2b]$$

The returns to off-farm work are exogenous and define the minimum payoffs to any activity that the household will accept. Thus, an increase in the wages paid for off-farm work lowers poaching effort, while an increase in the net expected payoffs from poaching p_T, or an increase in the density of tigers D, increases poaching effort.

Labor time spent on hunting prey animals is given by:

$$L_c = \frac{\alpha_x(w(L - L_g - L_T) + p_g G + p_T h_T)}{(w + \theta_x \Omega_x \delta X)}, \qquad [3a]$$

where

$$L_g = \left(\frac{w}{\beta p_g k(1 - \mu X)}\right)^{1/(\beta-1)}. \qquad [3b]$$

Substituting [3a] and [3b] in [1d] and aggregating over the N households, gives the total level of prey animals hunted:

$$H_x = N\delta L_x X. \qquad [3c]$$

The implicit price of hunting prey is again determined by the opportunity cost of time, which is defined by the off-farm wage rate. The hunted prey animals are consumed rather than sold, hence an increase in the wage rate has conflicting income and substitution effects on prey hunting levels (i.e.,

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[7] Unlike many other species, tigers are highly secretive animals inhabiting dense forests. Therefore the main poaching constraint is likely to be the difficulty involved in finding a tiger. Field studies suggest that the likelihood of an encounter depends on, *inter alia* the density of tigers and the amount of search effort (Karanth and Nichols 2000).These key features are captured in equation [1e].

[8] Note also that since the analysis focuses on subsistence households with limited incomes, we ignore the possibility that households may hire labor. In the absence of adequate data, we also ignore several other components of agricultural household behavior including: production and use of livestock (which may be preyed upon by tigers); different types of farm output; consumption of part of the farm output, and the use of other non-labor inputs (e.g., fertilizers).

[9] It is perhaps worth noting that such myopic behaviour has also been observed on communally held tribal lands where users own property rights to forest resources (Madhusudan and Karanth 1997)

$\partial H_x/\partial w > (<) \; 0)$. Specifically, the income effect of higher wages increases the demand for prey animals as a consumption good, while the substitution effect of higher off-farm wages raises the opportunity costs of time devoted to hunting prey. The net impact of higher off-farm wages therefore depends on the relative parameters of the model. In contrast, an increase in the price of agricultural goods, raises both income and the value of crops damaged by prey. This leads to increases in prey hunting levels ($\partial H_x/\partial p_g > 0$). Similarly, as expected, a reduction in the expected fine ($\theta_x\Omega_x$), or an increase in the crop damage coefficient (μ), both lead to higher levels of prey poaching (i.e., $\partial H_x/\partial(\theta_x\Omega_x) < 0$, $\partial H_x/\partial\mu > 0$).

This simple model of household behavior ignores a number of significant issues that are of relevance in the context of wild animal poaching in India.[10] For example, anecdotal evidence suggests that corruption amongst forest officials may be widespread in some tiger reserves in India (Breeden and Wright 1996). This is perhaps a consequence of the relatively low wages that are paid to forest officials—often in arrears. In the absence of data on the incidence of corruption, we do not explicitly deal with the modeling complications that arise when corruption is pervasive. However, it can be shown that the expected penalty for poaching in equation [1b] is formally equivalent to the reduced form payoff function that arises when poachers bribe corrupt officials.[11] The model also assumes that the probability of conviction is fixed. In practice, the probability of a successful prosecution is likely to depend on the level of expenditure by poachers on their legal defense and the attitudes of local magistrates to wildlife protection. Moreover, conviction rates and the formal penalties for poaching may not capture all the costs associated with being detected if caught poaching, suggesting considerable uncertainty in the payoffs to poaching.

IV. TIGER BIOLOGY

The use of a single equation to model population dynamics is often considered inap-

propriate for large predators that exhibit complex patterns of behaviour and face different mortality rates over various stages in their life cycle (see Burgman, Ferson, and Akcakaya 1993). Accordingly, the existing literature describes tiger population dynamics using stage based stochastic demographic models. In this paper, we follow this convention and extend the most recent model of tiger demography by Karanth and Stith (1999) to incorporate predator-prey interactions.

The Karanth-Stith model identifies tigers of both sexes, in four distinct demographic stages: cubs (younger than one year), juveniles (one to two years), transients (tigers older than two years in search of a home range), and adults (breeding tigers with a home range). In the absence of human pressures, mortality rates at each stage of the life cycle depend on intrinsic survival rates, which incorporate deaths from natural factors such as disease and intraspecific competition. For expositional ease, we begin by describing the dynamics of tiger populations when prey are plentiful and there is no poaching.

The number of cubs that survive in any year is determined by the birth rate of breeding females and the survival rate of cubs:

$$T_{t+1}^c = \sigma^c b T_t^{af}, \qquad [4a]$$

where subscripts denote time periods: T_{t+1}^c is the number of surviving cubs in period $t+1$; σ^c is the survival rate of cubs; b is the birth

rate per breeding adult female; and T_t^{af} is the number of breeding adult females. Following Karanth and Stith (1999), we assume an equal sex ratio at birth and mean litter size of three. The birth rate, b, is treated as a Poisson variable with a mean of three. Randomness is included in the model to capture demographic stochasticity.[12]

The surviving cubs move to the juvenile stage in the following period. The number of juveniles who survive is

$$T_{t+1}^{js} = \sigma^{js} T_t^{cs} \; (s = m, f), \qquad [4b]$$

where T_{t+1}^{js} is the number of surviving juvenile males (m) and females (f) in period $t + 1$, $\sigma^{js}(s = m, f)$ is the intrinsic survival rate of juvenile males (m) and females (f).

At two years, the surviving juveniles become transients. Transients are defined as adult tigers in search of home territories in which to hunt and breed. If a vacant home range is available, a transient immediately occupies the territory and is classified as a breeding adult. Let K^s ($s = m, f$) denote the maximum number of territories available for adults of gender $s = m, f$. Let T_t^{as} be the number of surviving adults of gender $s = m, f$ with existing home ranges. Then the number of vacant territories available for the transients to occupy is given by:

$$V_{t+1}^s = \text{Max}(0, K^s - T_t^{as})(s = m, f). \qquad [4c]$$

The number of transients in period ($t + 1$) is defined by: (*i*) the number of transients who survive from the previous period, (*ii*) juveniles who progress to the transient stage, (*iii*) minus the transients who find home ranges and thus exit to the breeding adult stage:

$$T_{t+1}^{\tau s} = \sigma^{\tau s}(\sigma^{js} T_t^{js} + T_t^{\tau s}) - V_{t+1}^s (s = m, f), \qquad [4d]$$

where $T_{t+1}^{\tau s}$ is the number of surviving transients in period $t + 1$, $\sigma^{\tau s}$ is the survival rate of transients of gender $s = m, f$.

Finally, the number of breeding adults is given by the existing number of surviving adults and the new recruits to the category of breeding adult:

$$T_{t+1}^{as} = (\sigma^{as} T_t^{as} + V_{t+1}^s), \qquad [4e]$$

where σ^{as} is the survival rate of adults of gender $s = m, f$. The total population of non-cub tigers (T) is defined to include the sum of juveniles, transients and adults, of both sexes. The model thus far assumes that prey are plentiful. The only constraints on population growth considered so far are the intrinsic survival rates and the amount of territory available to establish home ranges (i.e., K^s). If prey depletion lowers hunting success rates, it will lead to greater mortality of tigers. We therefore extend the model to take account of the impact of prey availability on tiger population growth.

Data on the intrinsic growth rates of individual prey species and the effects of browse and forage competition between species in tiger habitats is unavailable. Hence we adopt a simple approach and model the combined biomass of all prey species using a logistic equation of the form:

$$X_{t+1} - X_t = X_t r(1 - X_t/\bar{X}) - H_{xt} - \Psi_t, \qquad [5]$$

where X_t is the prey biomass at time t, r is the intrinsic growth rate, $\bar{X}$ is the prey carrying capacity of the forest, H_{xt} is the human harvest of the prey biomass defined in equation [3c] and Ψ_t is the harvest of the prey by tigers which is described below.

Field studies suggest that on average a tiger requires approximately 3,000 kg of prey per year to survive (Sunquist, Karanth, and Sunquist 1999). We therefore define the minimum food intake of a tiger as $M = 3,000$ kg. Field observations also reveal that tigers succeed in capturing between 10%–20% of the available prey biomass in their home ranges (Schaller 1967; Sunquist 1981; Johnsingh 1983). In the presence of competing predators such as wild dogs (*Cuon alpinus*) and leopards (*Panthera pardus*), a predation rate of 10% is deemed more appropriate (Karanth 2001). Thus, the predation rate is defined as $\rho = 0.10$. It follows that the maximum number of tigers that can be sustained with a prey base of X_t is: $\rho X_t/M$. Accord-

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[12] The random numbers were generated in Excel using a random seed of 1 and mean of 3.

ingly, the prey biomass consumed by tigers is given by:

$$\Psi_t = MT_t \text{ if } \rho X_t > MT_t$$
$$\Psi_t = \rho X_t \text{ otherwise,} \qquad [6a]$$

where T_t is the total number of tigers in period t, M is the minimum food intake and ρ is the predation rate.

Thus, when prey are plentiful (i.e., $\rho X_t > MT_t$), each tiger is able to meet its nutritional needs and successfully captures M kg of prey per annum, hence $\Psi_t = MT_t$. On the other hand, if there is insufficient prey to meet the needs of the total population, the level of predation is at its maximum level $\Psi_t = \rho X_t$.

A shortage of prey could have two effects on tiger survival prospects. First, prey depletion is likely to depress survival rates across all demographic stages. Second, a shortage of prey may also lower the carrying capacity of the habitat and thus lead to an expansion in the home ranges of breeding adult females. In the absence of data on the effects of prey depletion across demographic groups, we follow Karanth and Stith and assume that prey depletion effects only: (i) the carrying capacity of the habitat; and (ii) the survival rates of cubs. Thus, under conditions of prey depletion the survival rates of cubs and the carrying capacity are depressed by a prey depletion factor that is defined as:

$$\eta_{t+1} = \begin{cases} 1 & \text{if } \rho X_t - MT_t \geq 0 \\ \dfrac{\rho X_i}{MT_t} & \text{if } \rho X_t - MT_t < 0 \end{cases}. \qquad [6b]$$

The cub survival rate (σ^c) and the carrying capacity (K^s) are pre-multiplied by [6b].

It is acknowledged that the neglect of prey depletion effects on the survival rates across other demographic categories is unsatisfactory. This approach can therefore be expected to underestimate the true impact of prey depletion if survival rates are depressed more generally across all demographic stages. However, refinements of the model must await further research on this issue.

Turning next to the effects of poaching. Poachers target juveniles, transients, and adults. The number of tigers killed at each stage is assumed to be proportional to the existing distribution of tigers across the various demographic stages. Let superscript $i(i = j, \tau, a)$ denote demographic stages and recall that superscript $s = M, F$ denotes gender. Define κ_t^{is} as the proportion of male or female tigers at demographic stage $i(i = j, \tau, a)$. Then the number of gender s tigers poached at demographic stage $i(i = j, \tau, a)$ is defined as:

$$H_{Tt+1}^{is} = H_{Tt}\kappa_t^{is}, \qquad [6c]$$

where H_{Tt} is the total harvest of tigers as determined in equation [2b], $\kappa_t^{is} = (T_t^{is}/T_t)$ is the proportion of gender s tigers at stage $i(i = j, \tau, \alpha)$, $T_t^{is} =$ number of gender s tigers at stage i and T_t is the total population of tigers. The number of tigers at each stage is thus lowered by the amount defined in equation [6c].

V. SIMULATION RESULTS

We now combine the economic models of behavior (equations [2b] and [3c]) and tiger population growth (equations [4a]–[6c]) to determine the time paths of 'tiger stocks' under alternative scenarios. For given parameters, the level of poaching emerges from the optimising decisions of farmers and poachers. This in turn affects tiger stock levels. Model parameters are varied to determine the sensitivity of tiger population levels to changes in economic circumstances.

In the model labor is allocated across different activities until the marginal returns are equalised. The returns to off-farm work are exogenously fixed and hence define the minimum payoffs to any activity that a household will accept. The returns to agriculture vary with the price of agricultural commodities and the losses due to wildlife predation. The payoffs to poaching also vary with wildlife stocks and the expected penalties for conviction. It follows that changes in the returns to any one activity may induce a reallocation of labor across other activities and therefore could alter the level of poaching.

The parameters for the basic tiger population model (equations [4a]–[4e]) are from Karanth and Stith (1999), and are based on

field research in India and Nepal. Behavioral data for subsistence farmers are drawn from a variety of sources.[13] The Data Appendix provides details of the sources of information, assumptions, estimation methods and parameter values.

The benchmark simulation draws on parameter estimates based on the best available data for those regions with reasonably healthy tiger populations (e.g., the Kanha and Bandipur Tiger Reserves in India). The habitat is assumed to comprise an area of approximately 1,000 km^2 with a prey carrying capacity of 4,500 kg/km^2.[14] It is supposed that when prey are plentiful ($\rho X_t > MT_t$), the undisturbed habitat can sustain $K^f = 24$ breeding adult females and $K^m = 12$ adult males (Karanth and Stith 1999; Kenney et al. 1995). In the base case, farmers receive Rs 1,000 for each tiger killed, face a fine of Rs 25,000 and a 2% probability of conviction (WPSI 2001).[15] The off-farm wage rate is set at Rs 40 per day and the price of agricultural produce at Rs 8.5/kg. We begin by assuming a human population density of $N = 400$ households.

It is important to distinguish between the ecological effects and economic causes of prey depletion, from those of tiger poaching. In order to gain some understanding of these linkages, we begin by presenting simulations for the stylized case when only tiger poaching occurs. We then assume that there is no tiger poaching and consider the impact of prey poaching on tiger populations. Finally simulations are presented for the complete model where both tigers and their prey are hunted by subsistence farmers.

Consider first the effects of tiger poaching in isolation.[16] Curve A in Figure 1 shows the tiger population trajectory in a pristine habitat with no tiger poaching or prey depletion. The population achieves a stable equilibrium at 87 adult and juvenile tigers, suggesting a density of 9 tigers/100 km^2. This outcome approximates population levels in the fragmented, yet relatively healthy habitats found in India and Nepal. Curve B simulates the effects of tiger poaching when the parameters are at the base case levels.[17] The tiger population declines to a stable 53 adult and juvenile tigers, with poachers harvesting 6 tigers per

year (approximately 11 percent of the population). Curve C simulates the effects of a 50% increase in the price per tiger killed (Rs 1,500). The population falls substantially to 27 tigers, with 4 tigers harvested each year (approximately 12% of the population).

The simulation presented in Curve D illustrates the effects of an 80% increase in the price paid to tiger poachers. When the price is increased to Rs 1,800, the population declines to 19 tigers with 3 harvested each year. In curve E, when the poaching price is increased from Rs 1,800 to Rs 1,900, the tiger population collapses within 50 years.

This finding suggests that a relatively small increase in the payoffs to poaching (from Rs 1,800 to Rs 1,900) can drive a small population to extinction in a relatively short time period. This is a significant result, which is consistent with Karanth and Stith's (1999) simulations and related evidence that hunting of large felids can lead to sudden extinction when it exceeds a certain threshold level (Martin and de Meulanaer 1988; Bailey 1993). The impact of poaching may thus be discontinuous and prone to induce collapses in populations. This appears to be an example of the unstable equilibria frequently encountered in discrete time predator-prey

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[13] Many of the tiger reserves are in tribal areas. It seems likely that behavior of tribal agriculturalists would differ from those of other non-tribal agriculturalists. We have been compelled to use the only available data on agriculture, which is based on non-tribal agriculture. There is clearly an urgent need for fieldwork in and around tiger reserves to obtain more accurate information.

[14] The estimates of prey biomass in prime areas with tiger densities of between 10–12 per 100 km^2 is derived from data in Karanth and Nichols (2000). It is useful to note that this estimate is also consistent with earlier studies conducted using less advanced techniques. For instance, Johnsingh (1983) estimates a prey density of 3,382 kg/km^2 in Bandipur reserve and a predation rate of 30%, suggesting a possible carrying capacity of 3,382 (1 + 30%) = 4,397 kg/km^2.

[15] The assumption of a 2% conviction rate is a clear overestimate of the true conviction probabilities, our base case results thus underestimate the most likely consequence of poaching (WPSI 2001).

[16] Formally this can be achieved by setting all the coefficient of prey poaching to zero.

[17] In the base case farmers receive Rs 1,000 for each tiger killed, face a fine of Rs 25,000 and a 2% probability of conviction. N is fixed at 400 households.
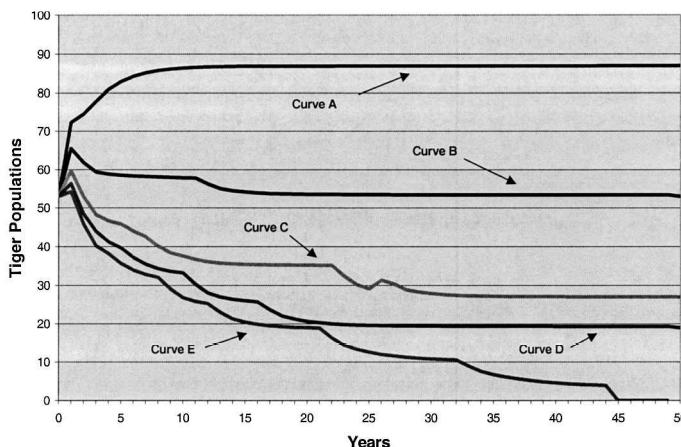
Parameter Values for Figure 1

|	Number of Farm Households	Wage (per day)	Tiger Poaching Price	Tiger Poaching Fine
Curve A	0	na	na	0
Curve B	400	Rs40	Rs1,000	Rs25,000
Curve C	400	Rs40	Rs1,500	Rs25,000
Curve D	400	Rs40	Rs1,800	Rs25,000
Curve E	400	Rs40	Rs1,900	Rs25,000

FIGURE 1

The Impact of Poaching Price on Tiger Populations

models, when the predator population is at low levels (May 1978, Freedman 1979). This finding has important policy implications since a large number of reserves have low tiger numbers of less than 30 animals per 1,000km². The simulations highlight the potential risks of extinction facing small tiger populations subjected to increased poaching pressure.

Figure 2 summarizes the consequences of prey depletion when there is no tiger poaching. Curve A shows the wild tiger population trajectories when the parameters are held at base levels in the model (ie, a farm population of 400 households; an off-farm wage of Rs 40 per day; and an agricultural output price of Rs 8.5/kg). In the base case, there is a stable population of 86 tigers that approximates that of a pristine habitat. When the number of farm households is increased by

50% (from 400 to 600) and off-farm wage and agricultural production prices are held constant at base levels, tigers are extinct in less than 60 years (Curve B). Higher human populations increase the demand for ungulates as a supplementary food source which leads to a shrinking prey base and hence a decline in the tiger population.

The model simulations further highlight the sensitivity of tiger populations to agricultural income. Even when the number of farm households is reduced to 500, if agricultural prices are increased by 20% (to Rs 10.2/kg), tiger populations are eliminated in less than 80 years (Curve C). On the other hand, Curve D shows that a 20% decline in agricultural prices leads to recovery of the population. This result helps illustrate how direct and indirect agricultural subsidies impact the environment and ecosystems. The responsiveness
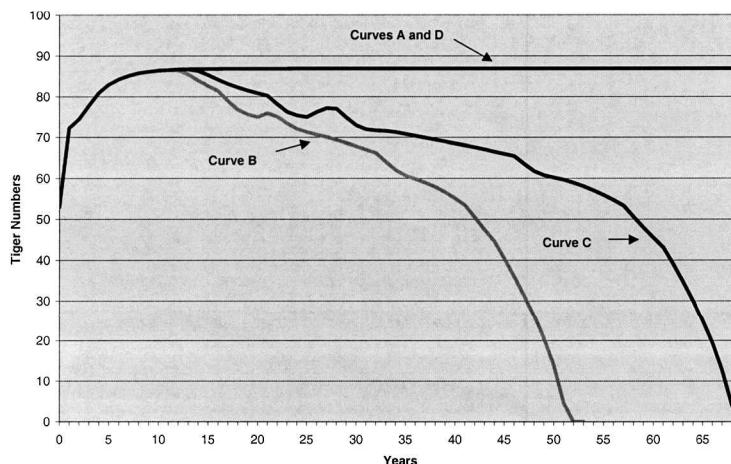
Parameter Values for Figure 2

|	Number of Farm Households	Wage (per day)	Agricultural Price (kg)	Prey Poaching Fine
Curve A	400	Rs40	Rs8.5	Rs5,000
Curve B	600	Rs40	Rs8.5	Rs5,000
Curve C	500	Rs40	Rs10.2	Rs5,000
Curve D	500	Rs40	Rs8.5	Rs10,000

FIGURE 2

THE IMPACT OF PREY POACHING ON TIGER POPULATION

of prey depletion to agricultural prices suggests that the withdrawal of agricultural subsidies may generate substantial improvements in habitat quality.

We also consider the effects of a 100% increase in off-farm wage when the number of households is set at $N = 500$, with all other parameters held at the base level. This simulation slowed the extinction time, suggesting that the substitution effects of higher off-farm wages do not reduce hunting levels sufficiently to outweigh the effects of a higher human population. This is clearly a consequence of the assumed parameter values in the simulations and highlights the need for more reliable parameter estimates based on field studies in tiger reserves. Finally, a 100% increase in either the fine for hunting or the probability of conviction both lead to recovery of the population (i.e., the population reaches the same levels as Curve D).

Figure 3 simulates the combined effects of both tiger poaching and prey poaching by subsistence farm households. In Figure 3, Curve A portrays the tiger population trajectory when all parameters are at their base levels. The population stabilizes at 53 tigers, with 6 tigers harvested each year. A common scenario faced by India's tiger reserves is increasing human population pressure. Curve B in Figure 3 simulates the impact on tiger populations when agricultural prices, tiger poaching prices and the number of farm households *all* increase by 50%. The result is that the reserve's tiger population is extinct in less than 45 years.

In Figure 3, Curve C, the fines for both prey poaching and tiger poaching are doubled to represent a reserve under pressure from human population. The tiger population stabilizes at 37 animals. The higher fines lower the payoffs from poaching both tigers
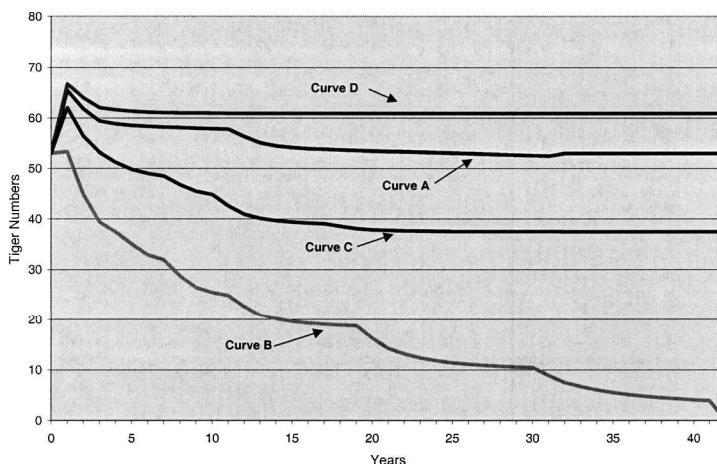
Parameter Values for Figure 3

	Number of Farm Households	Wage (per day)	Agricultural Price (kg)	Tiger Poaching Price	Tiger Poaching Fine	Prey Poaching Fine
Curve A	400	Rs40	Rs 8.50	Rs1,000	Rs25,000	Rs5,000
Curve B	600	Rs40	Rs12.75	Rs1,500	Rs25,000	Rs5,000
Curve C	600	Rs40	Rs12.75	Rs1,500	Rs50,000	Rs10,000
Curve D	600	Rs80	Rs12.75	Rs1,500	Rs50,000	Rs10,000

FIGURE 3

THE IMPACT OF TIGER POACHING AND PREY POACHING ON TIGER POPULATIONS

and their prey, so that effort devoted to hunting falls. On the other hand, if only the fine for tiger poaching is doubled, while the fine for prey poaching is held constant, the tiger population declines to zero in 54 years.[18]

The final simulation in Figure 3 (Curve D) doubles off-farm wages and the fines for tiger poaching and prey poaching. The result is a tiger population stabilizing at 53, with 5 killed each year. The increase in off-farm wages raises the opportunity costs of time allocated to poaching, while the higher expected fines lower the payoffs from hunting both tigers and their prey.

Figure 4 illustrates how households allocate labor to tiger poaching in each of the four scenarios presented in Figure 3. For example, Curve A in Figure 4 presents the same base case as Curve A in Figure 3 to demonstrate how the percentage of total household labor allocated to tiger poaching changes over time. Tiger poaching effort begins initially at just less than 25% of household labor allocation, declining gradually and stabilizing at around 7% with 6 tigers poached each year and the tiger population stable at 53.

For Curve B, agricultural prices, tiger poaching prices and total farm household numbers all increase by 50%. The initial tiger poaching effort is slightly more than 25% of household labor allocation; a higher initial allocation than the base case, reflecting the increased price for tigers. Simultaneously, increased agricultural prices, together with a higher farm population, leads to greater prey poaching and a reduction in the prey biomass, thereby lowering tiger survival rates.

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[18] This simulation, which has a population trajectory similar to Curve B, is not shown to avoid clutter.
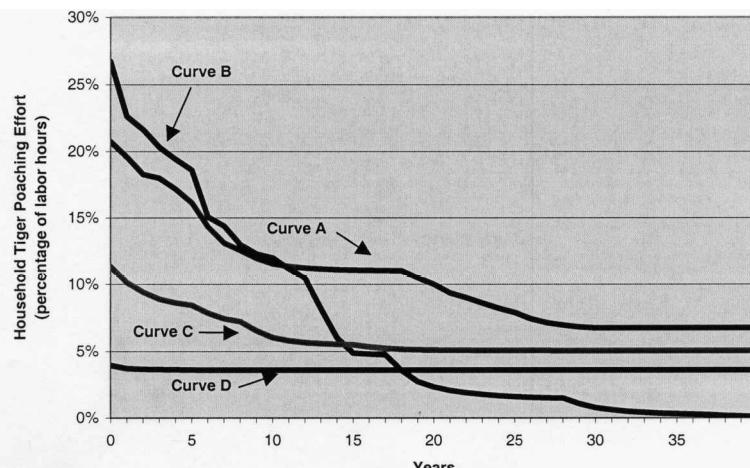
Parameter Values for Figure 4

|	Number of Farm Households	Wage (per day)	Agricultural Price (kg)	Tiger Poaching Price	Tiger Poaching Fine	Prey Poaching Fine
Curve A	400	Rs40	Rs 8.50	Rs1,000	Rs25,000	Rs5,000
Curve B	600	Rs40	Rs12.75	Rs1,500	Rs25,000	Rs5,000
Curve C	600	Rs40	Rs12.75	Rs1,500	Rs50,000	Rs10,000
Curve D	600	Rs80	Rs12.75	Rs1,500	Rs50,000	Rs10,000

FIGURE 4
HOUSEHOLD TIGER POACHING EFFORT

As tiger densities decline, the likelihood of finding a tiger decreases, so that the relative payoffs to labor allocated to hunting tigers falls. Hence the time allocated to hunting tigers declines to zero as the population reaches extinction in around 40 years.

Curve C uses the same parameter settings as Curve B except for the tiger poaching and prey poaching fines are doubled. The result is less household time devoted to hunting tigers as the expected cost of hunting increases due to the higher penalties. When off-farm wages and fines are doubled (Figure 4, Curve D), labor time devoted to tiger poaching declines and the tiger population stabilizes at more than 60. The increased fines together with a higher off-farm wage lower the relative payoffs from poaching and thus leads to lower levels of poaching.

We considered numerous other scenarios for the case of a reserve under increased pressure from human population and activities. The overall conclusion from a large number of simulations is that tiger populations in habitats with a healthy prey base are able to withstand modest levels of poaching. When the prey base is depleted, tiger survival prospects decline. Hence, recovery of the population necessitates controls over both the level of tiger and prey poaching.

These results indicate that anti-poaching policies should be directed at increasing the opportunity costs of poaching activities. In practical terms, this might involve higher fines, or more frequent and intensive patrols and other related policies that require greater avoidance by poachers, thus rendering poaching more difficult. These initiatives

would increase the opportunity costs of poaching. The provision of alternative sources of employment would also increase the opportunity costs of poaching, so long as it does not induce further migration into the area. The simulations suggest that higher off-farm wages when used in conjunction with other protective measures, would induce a rapid recovery of the tiger population (eg compare Curve C with D in Figure 3).

This outcome is suggestive of the reasons why tigers thrive in some prey abundant regions and not in others. In areas where the opportunity cost of poaching is high, due to effective patrols, for instance (e.g., the Kanha, Kaziranga, Nagarahole Tiger Reserves), tigers have survived in reasonable numbers. In more accessible and less protected landscapes, no tigers are found despite the existence of suitable habitats (Wikramanayake et al. 1998; Karanth 2001).

VI. CONCLUSION

This paper extends the existing biological literature on tiger populations by linking a stochastic demographic model of tiger population with household behavior that endogenizes two key threats to tiger populations: poaching tigers and poaching their prey. Alternative scenarios simulate the impact of the number of households, agricultural income, wage income, and poaching intensity of tigers and their prey. The results highlight the sensitivity, fragility, and instability of tiger populations to key economic parameters. Most notable is the finding that the level of human population is the most potent threat to the tiger's prey base and that the effects of large human populations may be difficult to reverse with the economic instruments considered in this paper.

The sensitivity of tiger populations to poaching incentives in prey depleted reserves is another important concern. Tiger populations appear to exhibit threshold responses to increases in poaching intensity. In particular, when prey levels are depleted, a relatively small increase in tiger poaching may trigger extinction. Thus, the control of poaching in prey-depleted environments remains a matter of critical concern. This suggests the need for increasing the conviction rates for poaching.

In practice, this may be difficult to achieve, for it requires major institutional and judicial reform accompanied by substantial investments in law enforcement.

The modelling results suggest that an alternative and potentially more effective way to reduce poaching is to increase the opportunity cost of poaching. Policies such as the provision of alternative employment and off-farm income, accompanied by controls on forest access, would have the desired effect of reducing the incidence of poaching.

The modelling results also raise questions about conservation efforts and forest management strategies that emphasize any type of forest resource use in and around tiger habitats, including JFM. The net social costs and benefits of alternative rural development strategies need to be examined. Examples include increasing non-farm and non-forestry employment, improving access to education, enhancing agricultural productivity, promoting non-forest dependent commercial activities and shifting private and public infrastructure investments away from tiger habitats. These are a formidable, yet urgently needed set of tasks, given that about two-thirds of India's total forest cover is in districts where the incidence of poverty (mostly among the tribal people) is more than 50 percent (Kumar et al. 2000).

A number of alternative measures have been suggested to tackle the problem of tiger poaching. These include strategies to reduce the demand for tiger products in traditional Oriental medicine and policies to control the illegal cross-border trade in tiger products which is controlled by criminal organizations (Nowell 2000). Captive breeding of tigers for the Oriental medicine trade in bones and organs is yet another suggestion which has gained some popularity. Support for this policy is based on the notion that generating supplies from captive–bred animals, commodity prices are expected to fall, thereby lowering the incentive to poach species in the wild. Damania and Bulte (2001) assess the prospects of captive breeding in considerable detail. The analysis reveals that when the illegal trade in wildlife commodities is controlled by cartelized oligopolies, captive breeding may lead to further poaching of wild stocks, as has occurred with the moon

bears of China and Vietnam and the crocodiles in Thailand (Meacham 1997). More important, however, these initiatives would do little to prevent extinction of tigers through depletion of their prey base.

The results in this paper are tentative. Lack of data and information on key economic and biological factors means that the model's parameters are based on imprecise estimates. To guard against exaggerating the threat of extinction we have adopted conservative assumptions. For instance, the probability of convicting poachers is assumed to be considerably higher than the available data suggests. Similarly, we use the upper bound of estimates for ungulate intrinsic growth rate and the lower bound of estimates for the returns to agriculture. Moreover, while prey depletion can be expected to ef-

fect survival prospects across all age classes, the model conservatively assumes that it has no impact on juvenile or transient tigers, but only depresses cub survival rates and the adult carrying capacity.

Finally, it is important to note that this paper ignores a number of other important threats to the tiger. Key amongst these is the unrelenting erosion of habitats and forest corridors connecting tiger reserves. Many tiger reserves are threatened with plans for major development projects including mines, roads and dams (World Bank 1996). The reserves face further pressures from the steady extraction of resources for timber, fuelwood, fodder, and livestock grazing, all of which are factors linked closely to human population growth. The effects of habitat erosion remain an area in need of urgent research.

DATA APPENDIX

DATA SOURCES AND PARAMETER VALUES

Parameter	Description	Value	Source
σ^{af}	Survival rate of adult female	.9	Karanth and Stith (1999)
σ^{am}	Survival rate of adult male	.8	Karanth and Stith (1999)
$\sigma^{\tau f}$	Survival rate of transient female	.7	Karanth and Stith (1999)
$\sigma^{\tau f}$	Survival rate of transient male	.65	Karanth and Stith (1999)
σ^{j}	Survival rate of juveniles	.9	Karanth and Stith (1999)
σ^{c}	Survival rate of cubs	.6	Karanth and Stith (1999)
ρ	Predation rate	.10	Karanth (1988)
M	Minimum prey biomass for tiger survival	3,000 Kg	Karanth (1988)
α_x	Coefficient for game meat demand in utility function. Based on proportion of meat in diet.	.05	World Bank/Nepal Nutrition and Energy Survey
L	Total endowment of labor per household	500 days per annum	Bluffstone (1995)
β	Coefficient in agricultural output production function	.154	Saha (1994)
μ	Damage to crops per unit prey biomass; calculated as percent crop loss per hectare/prey biomass. This data is based on survey work at Sariska Tiger Reserve.	.00001 per 1,000 Kg prey biomass	Sekhar (1998) tables 1–4
$\bar{X}$	Prey carrying capacity	4,500 kg/km^2	See text footnote 5
r	Prey intrinsic growth rate	.4	See text
δ	Coefficient of prey hunting production function	.002	Lower estimate from Kinyua et al. (2000)
θ_x	Probability of prey hunter being convicted	.001	See notes below
Ω'_x, Ω_T	Penalty for poaching prey and tigers	Rs5,000, Rs25,000	Wildlife Protection Act, India, 1972, Section 51
w	Daily wage rate for off-farm work	Rs40	Reserve Bank of India (1999)
p_g	Price of agricultural produce	Rs850/100 kg	Dinar et al. (1998)
P_T	Price paid to poachers for each tiger	Rs1,000	WPSI (2001)
θ_T	Probability of being convicted for poaching a tiger	.02	WPSI (2001)
λ, ξ	Parameters of tiger poaching production function	.46, 1.04	See notes below

1. Coefficients for the poaching production functions.

There are no studies on, nor data available on tiger poaching. We therefore seek to infer poaching production parameters using indirect proxies. One of the more sophisticated methods used to estimate tiger densities relies on a technique known as ''camera trap sampling.'' Cameras are positioned to sample an area within which some of the passing animals are photographed. The population estimates are based on the number of tigers photographed and the associated capture probabilities derived from the data (Karanth and Nichols, 1998, 2000). Many of the poaching techniques are ''passive'' and involve laying a snare or trap in areas where tigers are thought to reside. In the absence of any other information, we assume that that the main constraint on poaching is the difficulty involved in finding a tiger. It is supposed that the probability of a tiger being caught in a snare or trap is analogous to that of capturing a tiger with a camera in the area being sampled. Thus the probability of poaching is assumed to depend on the density of tigers and the number of days that a trap has been laid. We use information from the camera capture studies to proxy the poaching technology parameters. Using data from the most recent study (Karanth and Nichols 2000), we regress the number of tigers captured by cameras against trapping effort and tiger density to obtain the coefficients of the poaching production function:

$$Log(H_T) = .46 \; Log(Effort)$$
$$(24.09)$$
$$+ \; 1.04 \; Log(Density)$$
$$(4.41)$$

($R^2 = .80$, F = 21.244, SE of regression = 33, number of observations = 7, t-statistics in parentheses below the coefficients)

The estimates are based on data from the Pench, Kanha, Kaziranga, Nagarahole, Bhadra, Bandipur, and Ranthambore Tiger Reserves.

The parameters for poaching effort and density effects are based on these regression estimates. It is acknowledged that these estimates are at best only broadly indicative and likely to be biased. Moreover, it is difficult to determine the direction of the bias. If bait is more (less) efficient at capturing tigers than cameras, we will have underestimated (overestimated) the coefficient on effort and also biased the estimate of density. This is, however, the best available information.

The parameters used for the probability of detecting and convicting poachers are arbitrary. The Wildlife Trust of India (www. Wildlifetrustofindia.org) has recorded only two convictions for tiger poaching which suggests that the rate of conviction for poaching tigers may be lower than .02 (WPSI 2001). It is likely that the parameters used in this paper substantially overestimate the true probability of conviction. There is no published data on the conviction rates for poaching prey animals, though it is deemed to be lower than that for tiger poaching (Wildlife Trust of India, pers. comm.). A higher conviction rate is used than is suggested by the anecdotal evidence since actual convictions rates may not account for all the costs associated with detection and prosecution.

2. Off farm wages

Average rural wages in India vary from Rs 40 per day in some states (e.g., Haryana which has no tiger reserve) to Rs 22 in other states (e.g., Assam and Madhya Pradesh with tiger populations [Reserve Bank of India 1999]). We adopt the upper bound of these figures and set the off-farm wage rate at Rs 40, which is higher than the average wage in most tiger range states in India. Moreover, as noted by a referee, if rural wages fluctuate seasonally then poaching is likely to be concentrated in seasons of low labor demand and low wages. In this case, we are likely to have further overestimated the true off-farm wage in the off-peak seasons.

3. The Prey Intrinsic growth rate

Field data obtained by Karanth at Nagarahole suggests the following intrinsic growth rates for the major prey species: chital (*Axis axis*), 32%; gaur (*Bos gaurus*), 43%; wild pig (*Sus scrofa*), 150%. The aggregate prey growth rate weighted by estimated prey densities (see Karanth and Nichols 2000) yields an intrinsic growth rate of at least $r = 0.4$.

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