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Social diversity and ecological complexity: how an invasive tree could affect diverse agents in the land of the tiger

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ABSTRACT. A bioeconomic model is used to study the effect of *Prosopis juliflora*, an exotic tree, on diverse agents in Ranthambhore National Park. Tigers prey on wild herbivores, cattle, and goats that compete with each other to feed on green biomass, i.e. leaves and grass. There are four agents: goat owner, cattle owner, wood gatherer, and park manager. It is shown that there is an inherent trade-off between the number of tigers and village livestock that are grazing. *Prosopis juliflora* makes management of this trade-off more difficult. The four agents have different interests in the park, and a different ranking of the four scenarios that are simulated.

1. Introduction

Protected areas are natural assets that provide a range of goods and services. Protected areas in India, such as Ranthambhore National Park, have helped protect wildlife and biodiversity. However, local communities depend on such protected areas for a range of resources. In India, a survey of some protected areas in the mid-eighties revealed that 69 per cent had humans living within them, and grazing took place in 69 per cent (Bhatt and Kothari, 1997).

In Ranthambhore, the local villagers extract fuelwood, collect fodder, and graze their animals in the park. In order to meet the fuelwood demand of the villagers, and help reduce the 'incredible pressure', the forest department planted *Prosopis juliflora* in the Park (Rathore, 1984). However, the park managers did not foresee that this exotic tree would spread. Sippy and Kapoor (2001) report an estimated 4.8 per cent of the area of Ranthambhore National Park under *Prosopis juliflora*. This is causing concern to the Park authorities (GoR, 1999). *Prosopis juliflora* has affected the ecology in other

Professor Kanchan Chopra and Professor Partha Sen guided me. Dr Robert Scholes gave me equations relating to the productivity of plant biomass in semi-arid areas. The Ventana Corporation generously provided the Vensim software with which the model was simulated. Professor Karl-Goran Maler and Dr Anne-Sophie Crepin gave detailed comments, at the Ecological Economics Programme at ICTP, Trieste. Professor Charles Perrings and Dr David Simpson commented on preliminary versions of this paper. Three reviewers provided extensive and detailed comments.

areas quite significantly – for example, the Keoladeo National Park (Kaul, 2005) and the Banni grasslands in the state of Gujarat (Tewari *et al.*, 2000).

The research question that this paper seeks to answer is: what is the effect of biologically invasive *Prosopis juliflora* on diverse users in Ranthambhore National Park? Diverse agents – park manager, cattle owner, goat owner, and wood extractor – have different objectives. Their actions affect the ecology of the park, which in turn affects their benefits.

This specific case study of Ranthambhore National Park links up with two broader themes in natural resource management – social diversity and ecological complexity. *Prosopis juliflora* has dynamic effects on different economic agents because it is good for goats and wood and bad for cattle and wild herbivores (and therefore, for tigers). Different economic agents in turn affect it because it spreads faster if goats graze on it and can be cleared by those who value the tiger.

Studying the diversity of users is important. When the users of the resource have different interests in the resource, collective action can be rather hard to bring about (Baland and Platteau, 1996). In the case of protected areas in developing countries, the trade-off between local and global beneficiaries has been debated. While a substantial share of the benefits of protected areas are to national and foreign outsiders, a substantial share of the costs may be borne by locals who face restrictions on the use of natural resources (Murty, 1996; Kramer *et al.*, 1994).

Studying ecological complexity is important because management that ignores this complexity could be self-defeating. According to Brown (1997) there is a large interdependence between one natural resource and the rest of the ecosystem in wildlife habitat. This technical complexity makes the management of wildlife and habitat quite difficult. A biologically invasive tree further complicates matters. Invasive species have been a key threat to biodiversity loss (Perrings *et al.*, 2000).

Saberwal *et al.* (2000) point out that in two cases in India – Keoladeo Ghana and Valley of Flowers – the attempt to regulate human use of a protected area had an adverse effect. In both cases, the check on grazing helped increase weedy growth that decreased biodiversity.

How can social diversity and ecological complexity be studied? Chopra and Kadekodi (1999) distinguish between formal or analytical models and empirical or applied models. Two bioeconomic models that study the economics of developing country protected areas and use different modeling approaches are those of Skonhoft (1998) and Chopra and Adhikari (2004). While Skonhoft (1998) uses optimal control theory and solves his model analytically, Chopra and Adhikari (2004) first estimate equations of the system econometrically, and then simulate the system.

The question studied in this paper requires the development of a model that can link trees, grass, and *Prosopis juliflora* to cattle, goats, and tigers. Like the Skonhoft (1998) paper, in this paper also we attempt to model the competition between livestock and wild herbivores. However, this is modelled explicitly via competition for grass and leaves. Moreover, a distinction is made between cattle and goats, since they interact differently with *Prosopis juliflora*. Like the Skonhoft (1998) paper, the conflict between villagers and the park agency is explored. Unlike the

Skonhoft (1998) paper, this paper does not use optimal control theory. Nevertheless, optimization is used, which is explained later in the paper. Like Chopra and Adhikari (2004), this paper uses numerical simulation, and employs scenario analysis, in similar modelling software. Though not establishing relationships econometrically, this paper is informed by fieldwork and values of parameters are drawn, wherever possible, from empirical economic and ecological literature or from a survey carried out in the study area.

Section 2 provides a description of the study area, Ranthambhore National Park. Evidence from fieldwork and a survey about the different users of the Park are discussed. The characteristics of *Prosopis juliflora* and perceptions of this tree among villagers are described. Section 3 explains the structure of the model. Section 4 provides a discussion of the simulation of four scenarios. Section 5 concludes and discusses policy implications. An appendix describes the values used for the parameters.

2. Study area and context

Ranthambhore National Park is one of the best places in the world to see tigers in the wild. The tiger is the top predator in this National Park, and when it is protected a range of other animals and plants are also preserved. Ranthambhore National Park lies in the district of Sawai Madhopur in the state of Rajasthan (in India) on its eastern border with Madhya Pradesh. This is a semi-arid region – rainfall is on average about 800 mm, and the temperature ranges from 4°C to 47°C. The forests here are mainly of the tropical dry deciduous and dry mixed deciduous type, which in patches has been changed to dry deciduous scrub and grasslands by human activity. The tiger preys on such wild herbivores as sambar and nilgai.

Diverse users

Conversation with the park manager during fieldwork and examination of unpublished literature suggested the usefulness of examining different categories of users. In Ranthambhore, groups of graziers often go in with their cattle. A detailed study by Khan (undated) also pointed to some categories of users: the townships which he considers larger consumers of fuel wood than the villages, the cattle graziers who in the season after the monsoon left their cattle (mainly buffaloes) in the park, and the goat raisers who grew in number in the 1990s.

As part of the thesis from which this paper is drawn (Dayal, 2004), a survey of 227 households was conducted in January 2002. The survey of 227 households carried out by this author also helps identify different user categories. The category 'no use' (no use for fuel wood, fodder, or grazing) accounted for a little less than a third of the sample. The users who used the Park for fuel wood, fodder, and grazing accounted for 21 per cent of the total sample. And 20 per cent of the sample used the Park for both fuel wood and grazing.

Although the same household may carry out different activities, there are differences between households. In table 1 we see that the correlations between: (1) quantity of land owned, (2) firewood consumption, (3) number of bovines owned, and (4) number of goats owned, are low. The distribution

Table 1. *Correlations between quantity of land owned, firewood consumption, number of bovines owned, and number of goats owned*

	Land	*Firewood consumption*	*Number of bovines owned*	*Number of goats owned*
Land	1.00			
Firewood consumption	0.05	1.00		
Number of bovines owned	0.15	0.04	1.00	
Number of goats owned	−0.02	0.14	0.17	1.00

of goats, cattle, and land owned and fuel wood consumed among village households was studied by plotting Lorenz curves (plots of cumulative fraction of population against cumulative fraction of the variable of interest – Deaton, 1997). It was found that the ownership of goats was most concentrated among a few households, whereas bovines and land are moderately so, and fuel wood consumption is spread out more evenly among the households.

Village households are not completely heterogeneous since the same household may carry out cattle rearing, goat rearing, and wood gathering from the park. However, the villages are not completely homogeneous either, since livestock ownership is relatively concentrated in a few households. Thus, there is a case for examining resource management as it affects three types of villagers: goat owner, cattle owner, and wood gatherer. The actual villager will be some composite of these three, but different villagers will be more of one agent than the other.

Prosopis juliflora

The literature on *Prosopis juliflora* in particular and the *Prosopis* species in general helps us understand its effects on the ecology of the park. There are two views of *Prosopis juliflora* – one as a useful tree in harsh environments and the other as an invasive, thorny weed (Pasiecznik *et al.*, 2001). It has multiple uses, and can grow in very poor environments. Yet, the tree is also suspected by some observers to denude grassland ranges, invade water courses, and dry up rivers and water tables (Pasiecznik *et al.*, 2001).

According to Pasiecznik *et al.* (2001), there are three schools of thought about the spread of *Prosopis* in arid ecosystems:

1. Natural invasions. *Prosopis* plants create 'islands of succession' where they invade, aiding other plants to follow.
2. Weeds. *Prosopis* is a weedy species requiring eradication or control.
3. Soil fertility. *Prosopis* plants have an advantage where soil is deficient in nitrogen and therefore increasing soil fertility will check its spread.

Prosopis species, also called mesquite, cause considerable economic damage in the US, estimated at \$200–\$500 million per annum. In Queensland, mesquite could reduce pasture production by up to 90 per cent in some areas. As mesquite spreads in an area, it forms dense thickets that reduce pasture plants (DNRM, 1996). In the Indian state of Gujarat,

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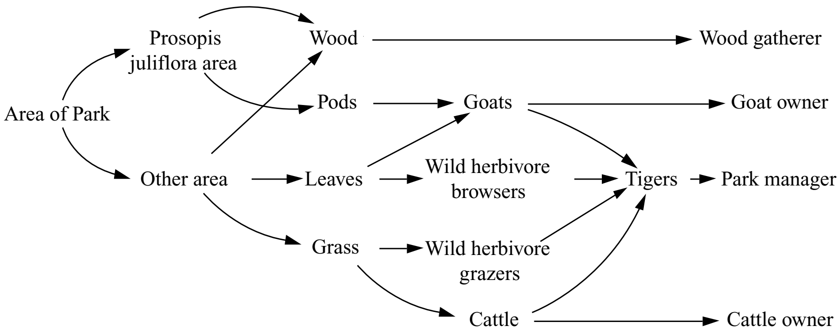

Figure 1. *Overview of model*

the Forest Department planted *Prosopis juliflora* on about 31,550 ha of Banni grasslands of Kutch. *Prosopis juliflora* spread rapidly – the area occupied by it increased from 378 km^2 in 1980 to 684 km^2 in 1992 (Tewari *et al.*, 2000).

Jacoby and Ansley (1991) argue that land managers should aim to manage, rather than eradicate, mesquite. There are four methods of controlling mesquite – biological, mechanical, chemical, and by fire. Control methods need to aim at destroying roots of mesquite because it coppices readily – i.e. it grows after the stem has been cut. If *Prosopis juliflora* is cut for fuel when the tree is less than two years old, it forms bushy thickets that are difficult to manage. While root ploughing can destroy *Prosopis juliflora* trees, after 10 to 15 years the trees in a dense stand grow back because there is a reservoir of seeds in the soil (Tewari *et al.*, 2000).

As part of the survey carried out, the village households were asked questions about their perceptions of *Prosopis juliflora*. The village households were asked about their use of *Prosopis juliflora*. A large majority, 89 per cent of the households in the sample, said they used *Prosopis juliflora* as a source of fuel. In contrast, only 6 per cent of the households said it was used as livestock feed – goats ate its pods. Seven per cent said that it destroyed fodder.

If we take a static view of the issue, *Prosopis juliflora* could appear to be a minor irritant, since it only occupies 4.8 per cent of the area of Ranthambhore National Park. However, in a dynamic perspective, given that *Prosopis juliflora* has been spreading in the park and is biologically invasive, it is important to explore the possible effects of *Prosopis juliflora* on the park and associated human agents. A bioeconomic model is used to do this. Since there is considerable uncertainty about the ecology–economy interactions, alternative scenarios or plausible future paths are examined.

3. Model overview and equations

Model overview

Figure 1 presents an overview of the model. The area of the Park is divided into *Prosopis juliflora* and 'other area'. *Prosopis juliflora* is spreading, and its growth increases with more intensive feeding of goats on its pods.

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Land under *Prosopis juliflora* can be cleared, and it then moves into the category 'other area'. Over time, *Prosopis juliflora* may enrich the soil, paving the way for ecological succession, which results in a gradual increase in 'other area'. Both *Prosopis juliflora* and 'other area' produce Wood. *Prosopis juliflora* also produces pods, which are eaten only by goats. Wild herbivore browsers and goats compete for leaf biomass produced by 'other area'. Wild herbivore grazers and cattle compete for grass produced by 'other area'. Wild herbivores, cattle and goats are assumed to follow a logistic growth function, with carrying capacity determined by the availability of feed. Tiger growth depends on prey hunted.

The main actors in the park were the park authorities and villagers. As discussed in section 2, there were differences among villagers, with the typical villager being a composite of goat owner, cattle owner, and wood gatherer. Hence, the four agents in the model are: wood gatherer, goat owner, park manager, and cattle owner. The wood gatherer, goat owner, and cattle owner derive benefits depending on the wood gathered, goats sold, or cattle either sold or used to produce milk.

We can divide the model into two components: ecology and economics. The ecology component can be further divided into the following sub-components: park-area composition, tiger prey, and tiger growth. The ecology component of the model is discussed now.

Ecology

The effect of *Prosopis juliflora* on the users of Ranthambhore National Park has been modelled by drawing on mathematical ecology. Since the effect of *Prosopis juliflora* on a National Park with tigers is being studied, a predator–prey model is used. The core of this model is the model of predator–prey interactions with density dependent prey growth and nonlinear predation, discussed in detail by Gurney and Nisbet (1998). The predator–prey model with density dependence and nonlinear predation is extended in this paper by (1) inclusion of several types of prey and (2) carrying capacity of the prey being linked to the dynamic composition of park area covered by *Prosopis juliflora* and other area.

Prosopis juliflora and Park area composition

The area of the park (A_{RNP}) consists of area under *Prosopis juliflora* (A_P), and other area (A)

$$A_{RNP} = A_P + A. \tag{1}$$

In section 2, the characteristics of *Prosopis juliflora* in terms of spread, effects, and control were discussed. This influenced the assumptions used in the equations related to it. The spread of *Prosopis juliflora* is assumed to follow a logistic function. *Prosopis juliflora* can also be cleared. When land is cleared, it moves from the category A_P to the category A. However, this is only partially successful – it will grow back. Hence

$$\frac{dA_P}{dt} = r_P A_P \left[1 - \frac{A_P}{k_P - N}\right] - 0.9 A_P f_{PC}, \tag{2}$$

where $k_P - N$ is the carrying capacity of area occupied by *Prosopis juliflora* at a point in time. k_P is the initial carrying capacity and N is the stock of nutrients. f_{PC} is the fraction of area under *Prosopis juliflora* that is cleared. The intrinsic rate of growth of *Prosopis juliflora*, r_P, is equal to a base rate of growth and an additional rate of growth that depends on the abundance of goats surviving on the *Prosopis juliflora* area

$$r_P = 0.025 + (0.025 \times X_5 / A_P \, g_P \, k), \tag{3}$$

where X_5 is the stock of goats surviving on *Prosopis juliflora* area and 'A_P g_P k' is the carrying capacity of goats surviving on *Prosopis juliflora* area (discussed later).

It is possible that *Prosopis juliflora* will give way to other vegetation after some time. It is leguminous, and enriches the soil. As the soil is enriched, other vegetation could find it easier to compete with *Prosopis juliflora*. It is assumed that the carrying capacity of *Prosopis juliflora* goes down as the stock of nutrients (N) added by it grows. The additions to the stock of nutrients are assumed to be proportional to the area under *Prosopis juliflora*

$$\frac{dN}{dt} = n \, A_P, \tag{4}$$

where n is a parameter. However, as the nutrient level increases and carrying capacity decreases, *Prosopis juliflora* gives way to other vegetation. If *Prosopis juliflora* is cleared, the process of addition to nutrient stocks is interrupted, and this delays the turning point of ecological succession.

Tiger growth

It is assumed that tiger (denoted by Y) growth is proportional to total predation by them, and death is proportional to the number of tigers

$$\frac{dY}{dt} = growth - death = [r_Y \, U \, Y] - \delta \, Y, \tag{5}$$

where U is the predation by each tiger, r_Y is the coefficient for tiger growth, and δ is the coefficient for tiger death.

There are five categories of prey that the tiger can prey on: wild herbivores that graze (X_1); wild herbivores that browse (X_2); cattle (X_3); goats that browse in land that has not been invaded by *Prosopis juliflora* (X_4); and goats that browse in land that has been invaded by *Prosopis juliflora* (X_5).

Holling explained the mechanisms underlying the search for prey. Tiger predation is assumed to follow a Holling type II function. The Holling type II function incorporates saturation and is therefore conceptually more satisfactory than a linear predation function. At the same time, it is simpler than a Holling type III or other relevant non-linear functions

$$U = u_M \frac{\sum X_i \varepsilon_i}{\left(a_H + \sum X_i \varepsilon_i\right)}, \tag{6}$$

where u_M is the maximum number of prey eaten per tiger and a_H is the half-saturation prey abundance. Cattle and goats are more difficult prey for the tiger to hunt (per unit of weight) than wild herbivores because they

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have human guardians. Accordingly the predation function takes this into account. The abundance of prey of type *i*, is given by $X_i\,\varepsilon_\iota$, where ε_i is the difficulty of hunting.

When prey is very scarce, the predator spends all its time searching and finds food at a rate which is directly proportional to its abundance. When prey is abundant, the predator is saturated – the rate of predation increases more gradually (Gurney and Nisbet, 1998).

Tiger prey

The equations for the tiger prey have a common structure

$$\textit{Net growth of tiger prey} = \textit{growth} - \textit{predation} - \textit{removal}$$

Growth of tiger prey is assumed to be logistic (as in Skonhoft, 1988), but growth incorporates the effects of competition. It is assumed that wild herbivore grazers compete with cattle, and wild herbivore browsers compete with goats that browse on 'other area'. Goats that browse on *Prosopis juliflora* land do not have competition from any other species. It is assumed that the intra-specific competition is equal to the inter-specific competition.

Predation of a species of tiger prey is in proportion to its weighted abundance relative to other prey of tigers.

Only cattle and goats can be removed, and sold.

Net growth of wild herbivores that graze (X_1) is given by

$$\frac{dX_1}{dt} = r_1 X_1 \left[1 - \frac{(X_1 + X_3)}{A g_G\, k}\right] - U\,Y \frac{X_1 \varepsilon_1}{\sum X_i \varepsilon_i}, \tag{7}$$

where r_1 is the intrinsic growth rate of wild herbivore grazers, and $A\,g_G\,k$ is the carrying capacity of wild herbivore grazers (g_G is the grass growth per-unit of area, and k is a parameter). At low levels of population of cattle and wild herbivore grazers, both wild herbivores and cattle grow at rates close to the intrinsic rate of growth. At higher levels of the combined population of wild herbivore grazers and cattle, there is less to graze on, and the rate of growth is lower.

Similarly, net growth of wild herbivores that browse (X_2) is given by

$$\frac{dX_2}{dt} = r_2 X_2 \left[1 - \frac{(X_2 + X_4)}{A g_L\, k}\right] - U\,Y \frac{X_2 \varepsilon_2}{\sum X_i \varepsilon_i}, \tag{8}$$

where r_2 is the intrinsic rate of growth of wild herbivore browsers, and $A\,g_L\,k$ is the carrying capacity.

Net growth of cattle (X_3) is given by

$$\frac{dX_3}{dt} = r_3 X_3 \left[1 - \frac{(X_1 + X_3)}{A g_G\, k}\right] - U\,Y \frac{X_3 \varepsilon_3}{\sum X_i \varepsilon_i} - O_C\,X_3, \tag{9}$$

where r_3 is the intrinsic rate of growth and O_C is the cattle removal fraction.

Goats browsing on 'other area' (X_4) are distinguished from goats feeding on *Prosopis juliflora* land (X_5)

$$\frac{dX_4}{dt} = r_G X_4 \left[1 - \frac{(X_2 + X_4)}{A g_L\, k}\right] - U\,Y \frac{X_4 \varepsilon_4}{\sum X_i \varepsilon_i} - O_G\,X_4, \tag{10}$$

where r_G is the intrinsic rate of growth of goats and O_G is the goat removal fraction

$$\frac{dX_5}{dt} = r_G X_5 \left[1 - \frac{X_5}{A_P\, g_P\, k}\right] - U\,Y \frac{X_5 \varepsilon_5}{\sum X_i \varepsilon_i} - O_G X_5, \tag{11}$$

where g_P is the pod growth per-unit of area.

Economics

There are four agents: the Park manager, the cattle owner, the goat owner, and the wood gatherer. The Park manager is assumed to maximize the total number of tigers in the next hundred years. On the basis of fieldwork and a reading of documents and literature, this appears to be a reasonable representation of the objective of the park manager.

The benefits of the categories of villagers over the period of time simulated is given by

$$\int B_i e^{-\rho t} dt, \quad i = C, G, W, \tag{12}$$

where ρ is the discount rate.

The cattle owner gets benefits from selling: (1) the cattle offtake (removal of cattle from stock for sale) and (2) milk from the cattle. The revenues from the sale of cattle offtake and milk are taken as a measure of benefits derived, in the absence of information on costs. Comparisons are made over different scenarios for each agent, and for this purpose such a proxy for benefits derived is adequate.

The benefits to the cattle owner, B_C, are given by

$$B_C = p_M\, m_F\, m_C\, X_3 + p_C\, O_C\, X_3, \tag{13}$$

where p_M is the price of milk, m_F is the fraction of cattle that are milk bearing, m_C is the milk yield per milk-bearing cattle, and p_C is the price of cattle. O_C, as mentioned before, is the offtake fraction of cattle.

The goat owner gets benefits from selling goats. Revenues from selling goats are taken as a measure of benefits to the goat owner

$$B_G = p_G\, O_G (X_4 + X_5). \tag{14}$$

The wood gatherer is assumed to only gather wood equal to the growth of wood stock. The model abstracts from the possibility that too much extraction could affect the stock of wood or overall composition of vegetation. Revenues from sale of this wood are taken as a measure of the benefits to the wood gatherer

$$B_W = p_W (w\, A + w_P\, A_P), \tag{15}$$

where w and w_P are the productivity of wood in land under non-*Prosopis juliflora* and *Prosopis juliflora* respectively.

4. Model simulations

Instead of optimizing the management of the park using optimal control, four scenarios explore the links between the ecology of the park and the different agents. These scenarios follow a two-way classification:

(a) *Prosopis juliflora* is cleared or not, and (b) tiger numbers are maximized over 100 years, or the benefits to cattle owners and goat owners are maximized.

The three control variables are: O_G (goat removal fraction), O_C (cattle removal fraction), and f_{PC} (*Prosopis juliflora* removal fraction). The goat removal and cattle removal fraction are chosen to be certain values at the beginning of the period to maximize an objective function that varies between scenarios. The goat removal and cattle removal fraction stay at that value through the 100 years of the simulation. In the case of the fraction of the *Prosopis juliflora* removed, this is done in the 15th year and the 60th year. Such a method of optimization is used to make the simulation in the Vensim software tractable. But this approach nevertheless yields useful insights.

The four scenarios are described in detail below:

- *Scenario 1. Tigers maximized, no Prosopis juliflora removed.* Number of tigers maximized over hundred years by choosing O_C and O_G, removal fractions of cattle and goats, respectively. In this scenario there is no removal of *Prosopis juliflora*, i.e. $f_{PC} = 0$. The park agency strictly enforces restrictions on livestock, but does not try to clear *Prosopis juliflora.*
- *Scenario 2. Cattle owner and goat owner benefits maximized, no Prosopis juliflora removed*. Cattle owner and goat owner's benefits (present value of benefits over hundred years) are maximized. For the cattle owner, who gets benefits from milk, maximum benefits follow when $O_C = 0$. The removal fraction of O_G is chosen so that the benefits to the goat owner are greatest, given $O_C = 0$. In this scenario there is no removal of *Prosopis juliflora*, i.e. $f_{PC} = 0$. The cattle owner and goat owner are not constrained by the park agency. They maximize their benefits over time by selecting the fraction of their livestock that they remove each year.
- *Scenario 3. Tigers maximized, Prosopis juliflora removed.* Number of tigers maximized over hundred years by choosing O_C, O_G, and f_{PC}, removal fractions of cattle, goats, and *Prosopis juliflora*, respectively. The park agency now clears *Prosopis juliflora.*
- *Scenario 4. Cattle owner and goat owner benefits maximized, Prosopis juliflora removed.* Cattle owner and goat owner's benefits (present value of benefits over hundred years) are maximized, along with that value of *Prosopis juliflora* removal fraction, f_{PC}, that maximizes the number of tigers (which is 1).

The model was simulated in the Vensim software.[1] The comparisons between the different scenarios provide an illustration of the trade-offs between the different agents, and the role of *Prosopis juliflora* in this trade-off.

Table 2 shows the values of the control variables in the different scenarios. In scenario 1 and scenario 2, there is no removal of *Prosopis juliflora*, so f_{PC} equals 0. In scenario 3 and scenario 4, there is maximum removal of *Prosopis*

[1] Vensim is a visual modeling software that can be used to build and run models of dynamic systems. Ford (1999) describes this and related software, and also the method of numerical simulation used in these software. The author will provide by email a copy of the model used in this paper to any one interested.

Table 2. *Control variable values in the four scenarios*

Scenario	*Prosopis juliflora removal fraction* f_{PC}	*Cattle removal fraction* O_C	*Goat removal fraction* O_G
Scenario 1	0	1	1.00
Scenario 2	0	0	0.16
Scenario 3	1	1	1.00
Scenario 4	1	0	0.14

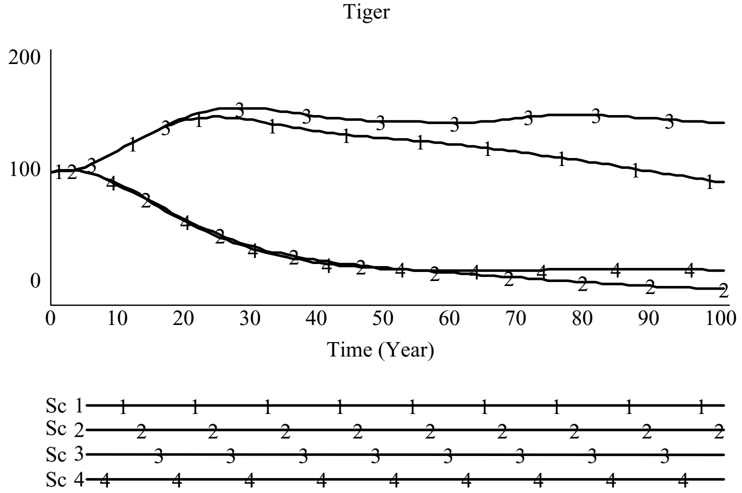

Figure 2. *Trajectories of number of tigers (y-axis) versus time (x-axis) in scenarios 1, 2, 3 and 4*

juliflora, so f_{PC} equals 1. In scenario 1 and scenario 3, the cattle removal fraction and the goat removal fraction are maximized, so O_C and O_G are both 1 in both scenarios. The cattle owner maximizes his benefits when O_C is 0, as in scenario 1 and scenario 3. The goat owner maximizes his benefits given f_{PC} is 0, and O_C is 0, in scenario 2 with a goat removal fraction, O_G, of 0.16. The corresponding O_G for scenario 4 is 0.14.

Figure 2 shows the number of tigers in the different scenarios. The number of tigers is greatest in scenario 3. In scenario 1, the park management does not clear *Prosopis juliflora* and the number of tigers dips relative to scenario 3. In scenarios 4 and 2 tiger maximization is not the objective. They have an almost identical trajectory of tigers until about the 70th year, after which the number of tigers dips in scenario 2.

The tiger is a top predator, and we now view graphs of trajectories of the lower components of the system (figure 3). In scenario 2, there is no removal of *Prosopis juliflora*, and the goat offtake fraction is low, so *Prosopis juliflora* spreads fast, but by about the 80th year it has added sufficient nutrients to start declining. In scenario 1, goats are removed from the system, so although *Prosopis juliflora* is not removed, it does not spread as fast as

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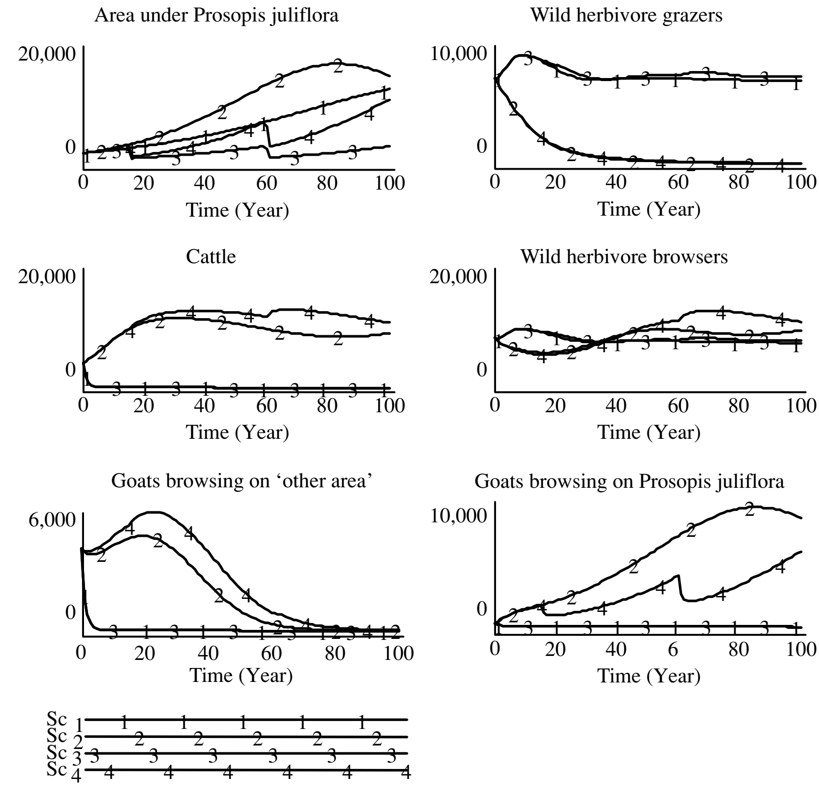

Figure 3. Trajectories of: area under *Prosopis juliflora (in hectares), wild herbivore grazers, cattle, wild herbivore browsers, goats browsing on 'other area', and goats browsing on Prosopis juliflora*

in scenario 2. The lowest trajectory is that of scenario 3, where goats are removed and so is *Prosopis juliflora*. In scenarios 3 and 4 the removal of *Prosopis juliflora* in the 60th year leads to a temporary sharp fall in levels of *Prosopis juliflora*.

Wild herbivore grazers and cattle compete for the same resource – grass on land that has not been invaded by *Prosopis juliflora*. Figure 3 shows that when cattle are not removed, as in scenarios 4 and 2, wild herbivore grazers are out competed and fall to low levels.

Wild herbivore browsers compete with goats feeding on 'other area' (land not invaded by *Prosopis juliflora*. The goat offtake fraction (O_G) is always more than zero. In scenarios 4 and 2 the population of goats feeding on 'other area' rises but then falls because of predation, positive offtake, competition from wild herbivore browsers, and the spread of *Prosopis juliflora*. Wild herbivore browser stocks tend to be relatively stable.

In scenarios 1 and 2 goats browsing on *Prosopis juliflora* are removed. In scenario 2, the area under *Prosopis juliflora* is greatest, and so is the stock of goats browsing on *Prosopis juliflora*.

Table 3. *Relative benefits to agents in the four scenarios (scenario 4 = 100)*

Scenario	*Park manager*	*Cattle owner*	*Goat owner*	*Wood gatherer*
Scenario 1	305	4	27	104
Scenario 2	93	92	120	112
Scenario 3	352	4	27	95
Scenario 4	100	100	100	100

Table 3 shows relative benefits to the four agents in the four scenarios (scenario 4 = 100). Only the comparison of scenarios within each column is valid; the columns cannot be compared with each other. We therefore order the scenarios by preference of each agent:

Park agency scenario ranking: 3 > 1 > 4 > 2
Cattle owner scenario ranking: 4 > 2 > 1,3
Goat owner scenario ranking: 2 > 4 > 1,3
Wood gatherer scenario ranking: 2 > 1 > 4 > 3

The four agents have different benefits in the four scenarios. The cattle owner has far less benefits in scenarios 1 and 3 than in 4 and 2. The goat owner has far less benefits when browsing is restricted compared to when it is not, but experiences greater benefits when *Prosopis juliflora* is not removed. The wood gatherer's benefits do not change much over the four scenarios. The benefits to the park manager change considerably when grazing and browsing by cattle and goats is restricted.

Bowles (2004) has suggested that interactions among social agents are mixtures of pure conflict and pure common interest. If we compare the relative benefits of the cattle owner and the park manager in different scenarios, we see that there is major conflict between them. Scenarios 2 and 4 are very much better for the cattle owner, and very much worse for the park manager compared to scenarios 1 and 3. There is a relatively minor amount of common interest between the cattle owner and the park manager – removal of *Prosopis juliflora* is in the interest of both the cattle owner and the park manager.

The park manager and the goat owner have a conflict of interest because the maximization of tiger numbers requires limited grazing by goats (comparing scenarios 2 and 4 versus scenarios 1 and 3). In addition there is a relatively minor conflict because removal of *Prosopis juliflora* is good for tigers and bad for the goats.

To model the socially optimal outcome, we need to weight the payoffs to the different agents. Because we do not have a monetary measure of the benefits received from tigers, it is not possible to show which outcome is socially optimal. Assuming that the gains to tiger preservation are high enough, there is a case for clearing *Prosopis juliflora*, and for compensating villagers for not using the park for grazing cattle or goats. If villagers are compensated adequately, and if the compensation is linked to the benefits from tiger preservation (via tourism receipts, for instance), it could be in their interests not to graze. However, individual villagers may be tempted

Table 4. *Relationships between parameters and benefits to individual agents*

	Benefits to			
Parameter	*Cattle owner*	*Goat owner*	*Park manager*	*Wood*
Relative ease of hunting cattle and goats	−	−	+	−
Instantaneous rate of growth of goats	−	+	−	+
Severity of invasion by *Prosopis uliflora*	−	+	−	+

to both avail of the compensation and graze their livestock, especially if monitoring and enforcement are weak.

Sensitivity to parameter values

First, the overall stability properties of the system modelled here are examined. Second, the effects of three key parameters on agent benefits are discussed. Third, the effect of small changes in the discount rate is mentioned.

Conditions for stability in the model in this paper are

$$\frac{d}{r_y U_m - d} \leq \frac{(g_L + g_G)Ak}{a_h} \leq \frac{r_y U_m + d}{r_y U_m - d}. \tag{16}$$

Below this range, the tiger cannot survive. Above this range, there are predator–prey oscillations. The middle term in equation (21) is the ratio of the carrying capacity of the prey (both grazers and browsers) to the half saturated prey abundance. According to Gurney and Nisbet (1998), the tendency towards oscillations in the system with increasing carrying capacity of the prey is often called the 'paradox of enrichment'. To study system behaviour above the range, a_h, the half-saturation prey abundance was changed from 15,000 to 9,000, which tipped the system into oscillatory mode. Oscillations are more frequent when the tiger levels are higher. However, there is very little change in the overall benefits to the different agents, and, more importantly, no change in the relative ranking of scenarios by the different agents.

Given the uncertainty about certain parameters, the sensitivity of benefits to the four agents to three key environmental factors were examined:

1. Relative ease of hunting cattle and goats compared to wild herbivores,
2. Rate of growth of goats
3. Severity of invasion of *Prosopis juliflora*

Fixing the cattle offtake fraction at 0.1, the goat offtake fraction at 0.3, and the *Prosopis juliflora* removal fraction at 0.7, models runs were carried out. We changed the level of one parameter at a time. Table 4 shows the relationships between parameters and benefits to individual agents.

The signs are as expected. The benefits to the park manager, for instance, are lower when it is more difficult for tigers to hunt cattle and goats, goats reproduce faster, and the *Prosopis juliflora* invasion is more severe. This has implications for the earlier discussion of scenarios. For example, if the invasion by *Prosopis juliflora* is more severe than expected, in scenarios 4 and 2 the tiger might die out in Ranthambhore National Park. Since there is great uncertainty, it is difficult to say how realistic this scenario is. Also, other factors that affect tiger survival could combine with *Prosopis juliflora* to knock the tiger out – disease, poaching etc.

Finally, the sensitivity to the discount rate was studied. The discount rate was lowered from 4 per cent to 2 per cent. The results do not change with a 2 per cent discount rate. Scenarios 1 and 3 do not change at all. In scenarios 2 and 4 the only change is a slight fall in the goat removal fraction (O_G).

5. Conclusions

This paper has explored the role of social diversity and ecological complexity in Ranthambhore National Park. There is an inherent trade-off between tiger numbers and village livestock grazing. If *Prosopis juliflora* is not removed, the number of tigers will be lower than if it is removed, *ceteris paribus*. If in addition to it not being removed, village livestock grazing is not restricted, the number of tigers could fall to perilously low levels.

The four agents have different rankings of the four scenarios. Restrictions on livestock grazing are good for the park manager (maximizing number of tigers) and very bad for the goat owner and cattle owner; and bad for the wood gatherer. *Prosopis juliflora* removal is good for the park manager and cattle owner, and bad for the goat owner and wood gatherer. The actual villager is a composite of goat owner, cattle owner, and wood gatherer; though, at present, more of one agent than another. Over such a long period, the villager would adjust to changing environmental conditions influencing relative attractiveness of different activities.

There is uncertainty about the severity of invasion by *Prosopis juliflora* (about its spread and about ecological succession). Also, the ease with which tigers can prey on livestock in comparison with wild herbivores is not known. At best, the invasion by *Prosopis juliflora* makes the park managers' task more difficult, and, at worst, substantial resources will be required to keep the tiger alive in Ranthambhore National Park.

Past research has suggested that mechanisms that enable local users to enjoy global benefits increase overall social welfare positively (Murty, 1996), and increases the stake in conservation (Skonhoft, 1998). The Communal Areas Management Programme for Indigenous Resources (CAMPFIRE) is a well-known initiative in Zimbabwe that has provided local villagers with incentives to protect wildlife (Tietenberg, 2003). However, in the specific context of the Ranthambhore National Park, where there is considerable uncertainty about how *Prosopis juliflora* could affect the Park, policy may have to go further than providing villagers with an incentive to further conservation goals.

Using the approach of 'adaptive management' in Ranthambhore National Park would be useful. This is a scientific management approach that explicitly emphasizes feedback learning. In this approach organizations and institutions can learn by experimenting, monitoring, and learning (Berkes and Folke, 1998).

Park managers will have to experiment with different ways of dealing with *Prosopis juliflora*, monitoring its effect on the rest of the system, and learning from experience. Park managers should make a distinction between different uses by villagers. Wood gathering of *Prosopis juliflora* could perhaps be encouraged, while goat grazing in the Park could be strictly discouraged. Tewari *et al.* (2000) maintain that due to a lack of knowledge, *Prosopis juliflora* has not been utilized in India to the extent that it could. The wood, pods, and other parts of the tree have several uses. Park managers have to assess how the utilization of the species furthers their conservation goals. At present the park authorities are aware of the possibilities of winning some local support by employing local villagers in the process of clearing *Prosopis juliflora* and distributing the wood. But this is only a beginning. The learning process will involve aiming to see how the tree is best cleared, what effect it is having on the native flora and fauna, and how best to get the greatest economic benefits from the *Prosopis juliflora* tree.

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Appendix: parameter values

Variable	*Symbol*	*Values, sources and comments*
Per-unit area production of grass	g_G	1.1 t/ha/y. Computed from equations by Scholes (2003) for interdependent production of biomass by grass and trees. The area in Ranthambhore National Park under different extent of tree canopy cover was taken into account.
Per-unit area production of leaves	g_L	1.2 t/ha/y. Computed from equations by Scholes (2003) for interdependent production of biomass by grass and trees. The area in Ranthambhore National Park under different extent of tree canopy cover was taken into account.
Per-unit area production of pods in *Prosopis juliflora* area	g_P	2.3 t/ha/y.
Area of Ranthambhore National Park	A_{RNP}	38,782 ha
Intrinsic growth rate of wild herbivores and cattle	r_1, r_2, r_3	The intrinsic growth rate was taken as 0.5, as in Ford's (1999) Kaibab deer herd model. This is a simplifying assumption.
Intrinsic growth rate of goats	r_G	Taken as 0.7. Goats breed faster than cattle; hence have a higher intrinsic growth rate.
'Maximum' number of prey eaten by each tiger	u_M	After consulting Karanth's (2001) note on tigers, we took u_M to be equal to 50 herbivores/year.
Relative difficulty of hunting cattle and goats compared to wild herbivores	ε_3, ε_4, ε_5	Taken as 0.2. As explained in the paper, cattle and goats have human protectors, and are therefore more difficult to hunt. Sensitivity of this parameter is discussed in the paper.
Coefficient for tiger growth	r_Y	0.01. Tiger growth is this coefficient times total predation times number of tigers. Calibrated.
Coefficient for tiger death	δ	0.25. Tiger death is this coefficient times number of tigers. Calibrated.
Parameter for estimating wild herbivore, goats and cattle carrying capacity	k	0.34. Calibrated
Price of cattle	p_C	Rs 8000, based on survey

Variable	*Symbol*	*Values, sources and comments*
Price of milk	p_M	Rs 10/litre, based on survey
Fraction of cattle that were milk bearing	m_F	0.25, based on survey
Milk yield per milk bearing cattle	m_C	10 litres/day, based on survey
Price of goat	p_G	Rs 1000, based on survey
Price of wood	p_W	Rs 1.75/kg, based on survey
Cost per unit *Prosopis juliflora* cleared	m_{PC}	Rs 8000/ha, forest department estimates
Rate of spread of *Prosopis juliflora*	r_P	Rate of spread of area under *Prosopis juliflora* taken as = 2.5% + 2.5% X_5/K_5 Tewari *et al.* report that it spread from 378 to 684 km^2 in Gujarat in 12 years. DNRM (1996) report on a study of mesquite increase at Santa Rita in exclosures that provided different degrees of protection from grazing animals over an 18 year period. Mesquite (*Prosopis* spp.) density was found to increase by 55% in exclosures that were grazed by cattle, but only increased by 24% when cattle were excluded.
Production of *Prosopis juliflora* wood per hectare of *Prosopis* land	w_P	*Prosopis juliflora* wood production taken as 3t/ha. Pasiecznik *et al.* (2001) 'when calculated over a 5–10 year rotation as would be expected for fuel wood harvesting, *P. juliflora* biomass production is generally in the range of 2–8 t/ha/yr, with plant densities of 400–2,500 trees/ha and in mean annual rainfall zones of approximately 400–800 mm without supplemental irrigation. (p. 84)
Production of wood per hectare from normal land	w	Using Scholes (2003) equations, estimated as 0.87t/ha/y.
Initial area under *Prosopis juliflora*	$A^P(0)$	Taken as 5%. According to data presented in Sippy and Kapoor (2001), 4.8% of area was under *Prosopis juliflora* in Ranthambhore National Park.
Discount rate	ρ	4%

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