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On the strategic stability of monitoring: implications for cooperative wildlife management programmes in Africa

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Game-theoretic modelling is used to study the design of an agreement among residents to conserve a wildlife resource, by not hunting animals illegally, when the community monitors its own behaviour. The analysis demonstrates that such an agreement may be very much costlier for a government to sustain if its incentive structure avoids the payment of monitoring fees, and instead relies on community benefits for conservation, with bonuses for reporting poachers. Conditions are identified for the agreement to be stable against both the temptation to avoid monitoring and the temptation to poach, either with guns or by snaring. In particular, the size of the community must exceed a critical value. Implications are discussed for community-based wildlife management programmes in Africa.

Keywords: common property resources; community-based management; cooperative behaviour; game theory; monitoring; wildlife conservation

1. INTRODUCTION

Examples abound of grazing lands, water supplies, and other common-property resources being managed successfully over long periods of time by self-governing associations of local users; see, for example, Berkes *et al.* (1989) and Bromley (1992). Recently, conservationists have advocated similar schemes through which local communities can manage the wildlife resources in the areas where they live (Child 1996). Devolving decision-making to the local communities is presumed to encourage sustainable resource use, although it is not inevitable; for example, when the Aché people of Paraguay were given ownership of their land, they immediately deforested the area (Hill & Hurtado 1996). Nevertheless, great success has been claimed for one of the first schemes of this kind, Zimbabwe's CAMPFIRE (Communal Areas Management Programme for Indigenous Resources) project (Child 1996).

Prior to the establishment of community-based wildlife management programmes, the authorities have often been especially concerned about local residents poaching, harbouring poachers, or failing to report poaching incidents. A common approach to addressing these concerns has been to employ local villagers as wildlife scouts to enforce the laws, while providing benefits at the community level from income-generating activities. These activities might include legal wildlife harvests, for sale or local consumption of meat, and trophy hunting, providing revenues from licence fees. Schemes vary as to whether they distribute the benefits in kind (as schools or grain-processing facilities, for example) or as cash payments. Poaching reduces the level of benefits received by community members by reducing the sustainable level of legal offtake of the wildlife resources. Community schemes have been shown to be effective in deterring poaching by local people (Lewis *et al.* 1990). For example, local people acting as auxiliary game guards have reduced rhino poaching in Namibia (Loutit & Owen-Smith 1989).

Most advocates of community-based wildlife management projects emphasize the importance of devolving decision-making as much as possible to the community level (Child 1996). Yet, Gibson & Marks (1995) make the important point that a resident's decisions concerning poaching and law enforcement are not dependent solely on community-level benefits from wildlife use. If wildlife is to be conserved in areas where people are living and hunting, rather than just in strictly protected areas, it is important that residents have an incentive to conserve their wildlife. Community-based wildlife management schemes are potentially powerful tools in this regard, but only if they are designed effectively.

Now, unlike in protected areas (where there is an asymmetry of role between scout and poacher), in a community-based scheme such as CAMPFIRE, each resident must decide both whether to poach and whether to enforce the law. In other words, there is symmetry with regard to roles. On the one hand, each individual has two ways to cheat: in the role of resident, by poaching, and in the role of potential scout, by electing not to monitor the resource. On the other hand, each individual can instead opt both to monitor the resource and to refrain from poaching. Our goal is to clarify how economic parameters influence these potential outcomes. In particular, we seek conditions for mutual enforcement of a conservation agreement to be strategically stable within a

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community, against the temptation to poach. We approach this issue in terms of game theory. A list of symbols used in our model appears in Appendix A.

Before proceeding, we wish to emphasize that we discuss only the temptation for local residents to poach, and the corresponding requirements for strategic stability of community-based management schemes. Poaching by organized gangs from outside a local area is not amenable to such an analysis, particularly if the gangs are from another country, as was the case when rhinos were poached by Zambians in the CAMPFIRE areas of Zimbabwe (Milliken *et al.* 1993). That is not to say that these issues are not significant. On the contrary, animals with internationally traded, high trophy values are both potentially important to the revenue-generating ability of community management schemes, and particularly vulnerable to external forces. Although local populations may be able to monitor such poaching incursions, they are ill-equipped to deal with the heavily armed and well-organized gangs that target elephants and rhinos (Leader-Williams & Milner-Gulland 1993). Nevertheless, these issues fall outside the scope of our analysis.

2. MATHEMATICAL MODEL

Let a community consist of $n+1$ decision-making families or individuals, to whom a government is offering incentives to conserve a wildlife resource. For the sake of simplicity, we assume that incentives are offered in cash, thus finessing the issue of how non-cash benefits can be equitably distributed among deserving individuals. The maximum potential community benefit per period for conserving the resource is B. It is paid in full if no individual is hunting illegally, but reduced proportionately to zero as the number of poachers rises from zero to $n+1$; in any event, it is distributed equally among all individuals. Thus the community 'wage' per period to each individual for conserving wildlife when m individuals are poaching is

$$W_m = \frac{B}{n+1}\left(1 - \frac{m}{n+1}\right). \tag{1}$$

A choice of hunting technologies is available to residents. For example, in the Luangwa Valley of Zambia, they may either snare surreptitiously or hunt with guns. Before recent increases in law enforcement levels, hunting with guns was preferred. However, recently, snaring has become more prevalent, due to its lower probability of detection (Freehling & Marks 1998). We use these two technology options as examples of the trade-offs a poacher may face, denoting them as 'L' for hunting with guns, a long-range technology, and 'S' for hunting with snares, a short-range technology.

Let V_Z be the expected value of returns per period from using type-Z technology, let D_{iZ} denote the associated probability of being detected if i individuals are monitoring; and let C_Z denote the corresponding expected cost per period of a conviction for poaching. Then the expected benefit per period to each individual who poaches with type-Z technology, if i individuals are monitoring, is

$$Z_i = V_Z(1 - D_{iZ}) + (V_Z - C_Z)D_{iZ} = V_Z - C_Z D_{iZ},\ Z = L,S. \tag{2}$$

For the sake of simplicity, we assume that each monitor has a constant probability q_Z per period of observing while type-Z technology is used. Thus, the probability that some monitor is observing, i.e. the probability that not all monitors are not observing, is

$$D_{iZ} = 1 - (1 - q_Z)^i, \quad Z = L,S. \tag{3}$$

Because long-range technologies typically have a higher probability of detection (see above), we assume that

$$q_L > q_S. \tag{4}$$

It should perhaps be emphasized that C_L and C_S are expected monetary costs per period, based on an individual's perception of costs of potential outcomes before any offence is committed. Many conditional probabilities could, in principle, influence the probability of being convicted, once observed (e.g. conditional probabilities of capture once observed, prosecution once captured, conviction once prosecuted, etc.), and the outcome of a conviction might be a prison sentence; but it is possible to place an expected monetary value on the penalty received. For example, prison sentences can be converted to fines using magistrates' recommended prison sentences for an offender who defaults; see Milner-Gulland & Leader-Williams (1992).

The existence of a community wage ensures that the net value of poaching with type-Z technology is less than V_Z. When m individuals are poaching, an additional poacher reduces the community wage by $W_m - W_{m+1} = B/(n+1)^2$. Thus, the net expected value per period of poaching with type-Z technology is

$$v_Z = V_Z - \frac{B}{(n+1)^2},\ Z = L,S. \tag{5}$$

If v_L and v_S were both negative, then there would be no incentive to poach. The persistence of poaching suggests, however, that one of them is positive, i.e.

$$\max(v_L, v_S) > 0. \tag{6}$$

Expected returns, V_Z, depend not only on the value of captured animals, but also on the numbers taken per period with type-Z technology. Accordingly, it will be convenient to denote the higher value technology by H, regardless of whether $H = L$ or $H = S$, and the other technology by O (so that $H = L$ implies $O = S$, and vice versa). Then inequality (6) is equivalent to $v_H > 0$.

We assume that each individual who monitors is paid a scouting fee f by the government. As discussed at the end of the paper, we envisage that this payment would be remuneration for a variety of monitoring duties (e.g. censusing), of which game law enforcement is only one; thus, monitors would have useful work to do, even if no one was breaking the law. We assume that monitors would always report observed violations to the government, for which there would be an additional reward R_Z to the first informant of a type-Z infraction (Jachmann & Billiouw 1997). Monitoring is not without its costs, however; even if no one is poaching, there is an opportunity cost c_0

associated with the remaining duties. Furthermore, reporting poachers to the government could incur opprobrium, so that expected disutility of monitoring increases with the amount of poaching. We assume that the marginal disutilities with respect to numbers of users of type-L and type-S technology are c_L and c_S, respectively. Thus, with j type-L poachers and k type-S poachers, the total expected cost of monitoring is $c_0 + c_L j + c_S k$ per period. Given that hunters gain social status from providing their lineage dependents with meat and goods exchanged for meat (e.g. Gibson & Marks 1995, p. 943), c_L and c_S are probably much larger than c_0, which is probably very small. Accordingly, we expect

$$c_L \gg c_0, \;\; c_S \gg c_0, \;\; c_0 \approx 0. \tag{7}$$

Observing a violation is not the same thing as being rewarded for it, however, because there may be more than one observer, and only the first to report an offence is assumed to be remunerated. Thus, for a monitoring individual, the probability of obtaining a reward from a specific violation is the probability that the violation is detected multiplied by the conditional probability that the monitor is first to report it. For the sake of simplicity, we assume that all monitors are equally likely to obtain a reward from each violation. Then the reward probability for type-Z technology is D_{iZ}/i, where i is the number of monitors. Note that this quantity is approximately equal to q_Z when q_Z is small (that is, when there is effectively no competition in the race to report). Combining our results, we find that the expected benefit per period to each monitoring individual, when j other individuals are engaged in type-L poaching, k other individuals are engaged in type-S poaching and i individuals are monitoring, is

$$M_i^{jk} = \frac{(jR_L D_{iL} + kR_S D_{iS})}{i} + f - c_0 - c_L j - c_S k. \tag{8}$$

We assume that poachers may use either type-L or type-S technology, but not both. Thus, each individual has six possible strategies (see table 1). (We justify restricting the number of strategies to six in the discussion at the end of the paper.)

By analogy with Mesterton-Gibbons (1993, pp. 132–135), we model the strategic interaction as a symmetric $(n+1)$-player game, reduced to an effectively two-player game by supposing that a focal individual interacts with a population consisting of the remaining n individuals, assumed identical. Player 1 is the focal individual, and player 2 is the population. Symmetry implies that the focal individual is arbitrary.

In terms of table 1, a state of large game decimation without law enforcement broadly corresponds to a population norm of LX; a state of reduced exploitation, in which improved law enforcement induces exploiters to take small game only, broadly corresponds to a population norm of SM; and a state of conservation and law enforcement corresponds broadly to a population norm of NM. In essence, therefore, the thesis of Gibson & Marks (1995) is that the community-based wildlife management scheme operating in the Luangwa Valley, Zambia, has failed to achieve its desideratum of NM, but instead has evolved from a norm of LX in the 1970s and 1980s to a norm of SM in more recent times. The goal of our analysis is to indicate how the desired outcome could yet be attained.

Table 1. *The strategy set*

#	strategy	definition
1	LM	poach with type-L technology, monitor and report (other) lawbreakers
2	LX	poach with type-L technology, do not monitor or report lawbreakers
3	SM	poach with type-S technology, monitor and report
4	SX	poach with type-S technology, do not monitor or report
5	NM	do not poach, monitor and report
6	NX	do not poach, do not monitor or report

3. CONDITIONS FOR STRATEGIC STABILITY

A strong (symmetric) Nash equilibrium strategy of such a game is a population strategy that is uniquely the focal individual's best reply to it. Mathematically, this strategy is the restriction to a finite population of the concept of a strong evolutionarily stable strategy, or ESS (Maynard Smith 1982). The ESS analogy is instructive: we can think of the focal individual testing various alternative strategies against the population strategy. If any of these alternatives is a better reply, then other individuals can be expected to copy it, so that it increases in frequency, or 'invades'; whereas if none of the alternatives is a better reply, then the focal individual can be expected to conform to the norm of the population. We will refer to a stable population norm as a stable strategy.

The matrix of rewards per period to a focal individual, using a given row strategy against a population using a given column strategy, can now be determined from expressions (1)–(3), (5) and (8), and is shown in table 2. We will denote this matrix $\mathbf{A}$, so that a_{IJ} is the reward to an individual using strategy I against n individuals using strategy J. For example, the reward to strategy NX against population strategy LM is $a_{61} = W_n$ because strategy NX neither poaches nor monitors: the only benefit is the community wage, which is W_n, because there are $n + 0 = n$ type-L poachers and no type-S poachers among the $n+1$ individuals in the entire population. Similarly, the reward to strategy SM against population strategy SX is $a_{34} = W_{n+1} + S_0 + M_1^{0n}$, which we obtain as follows. First, because there are $n+1$ type-S poachers when strategy SM confronts n individuals using strategy SX, the community wage is W_{n+1} $(=0)$. Second, because SX does not monitor and SM does not monitor itself, no one monitors the SM-strategist, so that the expected benefit of poaching is S_0. Finally, the benefit from monitoring is M_1^{0n}, because the focal individual is the only monitor; and although all $n+1$ individuals are poaching, the focal individual does not monitor itself. Note that the benefits of monitoring to the focal individual are independent of the number of monitors if no one else is poaching, as indicated by the subscripted dots in columns 5 and 6 of the reward matrix.

Table 2. *The reward matrix*

	LM	*LX*	*SM*	*SX*	*NM*	*NX*
LM	$W_{n+1} + L_n + M_n^{n0}$	$W_{n+1} + L_0 + M_1^{n0}$	$W_{n+1} + L_n + M_n^{0n}$	$W_{n+1} + L_0 + M_1^{0n}$	$W_1 + L_n + M_{...}^{00}$	$W_1 + L_0 + M_{...}^{00}$
LX	$W_{n+1} + L_n$	$W_{n+1} + L_0$	$W_{n+1} + L_n$	$W_{n+1} + L_0$	$W_1 + L_n$	$W_1 + L_0$
SM	$W_{n+1} + S_n + M_n^{n0}$	$W_{n+1} + S_0 + M_1^{n0}$	$W_{n+1} + S_n + M_n^{0n}$	$W_{n+1} + S_0 + M_1^{0n}$	$W_1 + S_n + M_{...}^{00}$	$W_1 + S_0 + M_{...}^{00}$
SX	$W_{n+1} + S_n$	$W_{n+1} + S_0$	$W_{n+1} + S_n$	$W_{n+1} + S_0$	$W_1 + S_n$	$W_1 + S_0$
NM	$W_n + M_n^{n0}$	$W_n + M_1^{n0}$	$W_n + M_n^{0n}$	$W_n + M_1^{0n}$	$W_0 + M_{...}^{00}$	$W_0 + M_{...}^{00}$
NX	W_n	W_n	W_n	W_n	W_0	W_0

A population strategy is stable if its diagonal element in table 2 is the largest in its column. In other words, strategy J is stable if a_{JJ} exceeds a_{IJ} for all $I \neq J$; or equivalently, if the only non-positive term in column J of the population stability matrix

$$\mathbf{P} = \begin{pmatrix} 0 & a_{22}-a_{12} & a_{33}-a_{13} & a_{44}-a_{14} & a_{55}-a_{15} & a_{66}-a_{16} \\ a_{11}-a_{21} & 0 & a_{33}-a_{23} & a_{44}-a_{24} & a_{55}-a_{25} & a_{66}-a_{26} \\ a_{11}-a_{31} & a_{22}-a_{32} & 0 & a_{44}-a_{34} & a_{55}-a_{35} & a_{66}-a_{36} \\ a_{11}-a_{41} & a_{22}-a_{42} & a_{33}-a_{43} & 0 & a_{55}-a_{45} & a_{66}-a_{46} \\ a_{11}-a_{51} & a_{22}-a_{52} & a_{33}-a_{53} & a_{44}-a_{54} & 0 & a_{66}-a_{56} \\ a_{11}-a_{61} & a_{22}-a_{62} & a_{33}-a_{63} & a_{44}-a_{64} & a_{55}-a_{65} & 0 \end{pmatrix} \tag{9}$$

is $p_{JJ} = 0$.

The first two columns of the matrix $\mathbf{P}$ are shown in table 3*a*, the next two columns in table 3*b*, and the last two columns in table 3*c*. Some general results emerge at once. First, because

$$p_{21} + p_{12} = R_L(1 - (1 - q_L)^n - nq_L) \leqslant 0 \tag{10}$$

for $n \geqslant 1$, if p_{12} is positive then p_{21} is negative, and vice versa. Thus, if either LM or LX is a stable strategy, then the other is not a stable strategy: if conditions do not favour a switch to monitoring in a no-monitoring population, then they also must favour a switch to no monitoring in a monitoring population, and vice versa. Similarly, SM and SX cannot both be stable strategies because $p_{43} + p_{34} \leqslant 0$; NM and NX cannot both be stable strategies because $p_{65} + p_{56} = 0$; LX and SX cannot both be stable strategies because $p_{42} + p_{24} = 0$; and only one of LM, SM and NM can be stable because $p_{51} + p_{15} = 0$, while both $p_{31} + p_{13} = 0$ and $p_{53} + p_{35} = 0$. Furthermore, and unsurprisingly, NX cannot be a stable strategy, because inequality (6) implies that either p_{26} or p_{46} is negative: lack of vigilance favours poaching. The upshot is that at most two strategies can be stable strategies; and if there are two stable strategies, then one must be a monitoring strategy (LM, SM or NM) while the other must be a no-monitoring strategy (LX or SX). Indeed, if one of these two no-monitoring strategies is stable, then it must be to use the higher-value technology (i.e. strategy HX), for if everyone else were using the lower value technology (i.e. strategy OX) then it would pay to switch.

Our purpose, however, is to find conditions for NM to be stable, which can happen only if $p_{65} > 0$ or

$$f > c_0. \tag{11}$$

In particular, f must be positive: *each individual must be paid to monitor even if no one poaches, or else the agreement is unsustainable.* On the other hand, in view of (7), f need not be large to satisfy inequality (11).

We assume for the remainder of this section that inequality (11) holds. Then $p_{45} > p_{35}$, and $p_{25} > p_{15}$. So NM is a stable strategy if, and only if, p_{15} and p_{35} are both positive or, on using equation (5) in table 3*c*,

$$(1 - (1 - q_H)^n)\frac{C_H}{V_H} + \frac{1}{(n+1)^2}\frac{B}{V_H} > 1 \tag{12}$$

and

$$(1 - (1 - q_O)^n)\frac{C_O}{V_O} + \frac{1}{(n+1)^2}\frac{B}{V_O} > 1 \tag{13}$$

(where H denotes the higher-value technology and O the other type); by equation (5), the second inequality is automatically satisfied if v_O is negative. As remarked above, the only other potentially stable strategy is HX. From table 3*a*, if $H = L$, i.e. $V_L > V_S$, then to exclude the possibility that LX is stable we require $p_{12} < 0$ or $n(c_L - q_L R_L) < f - c_0$; whereas if $H = S$, then to exclude the possibility that SX is stable we require $p_{34} < 0$ or $n(c_S - q_S R_S) < f - c_0$. So NM is the only stable strategy if, in addition to inequalities (11) and (12), we have

$$n(c_H - q_H R_H) < f - c_0. \tag{14}$$

Ignoring the fanciful circumstance that the marginal disutility of monitoring for a type-H infraction almost exactly balances the probability of observing one times the reward for reporting it ($c_H - q_H R_H \approx 0$), the above inequality cannot be satisfied for positive $c_H - q_H R_H$ unless either $f - c_0$ is infeasibly large or n is unreasonably small. In practice, therefore, NM is the only stable strategy if inequalities (11), (12) and

$$q_H > \frac{c_H}{R_H} \tag{15}$$

are all satisfied.

Because $1 - (1 - q_H)^n$ cannot be less than q_H (for $n \geqslant 1$), inequality (12) must be satisfied if $q_H C_H / V_H > 1$. Similarly, inequality (13) must be satisfied if $q_O C_O / V_O > 1$. But it is also satisfied if $v_O < 0$. Thus, sufficent conditions for NM to be the unique stable strategy are $f > c_0$,

Table 3. *Type-L (a) and type-S (b) technology, and (c) no-poaching columns of the population stability matrix*

(*a*)

I	p_{I1}	p_{I2}
1	0	$-f + c_0 + n(c_L - q_L R_L)$
2	$f - c_0 - nc_L + D_{nL}R_L$	0
3	$V_L - D_{nL}C_L - V_S + D_{nS}C_S$	$V_L - V_S - f + c_0 + n(c_L - q_L R_L)$
4	$V_L - D_{nL}(C_L - R_L) - V_S + D_{nS}C_S + f - c_0 - nc_L$	$V_L - V_S$
5	$v_L - (1 - (1 - q_L)^n)C_L$	$v_L - f + c_0 + n(c_L - q_L R_L)$
6	$v_L - D_{nL}(C_L - R_L) + f - c_0 - nc_L$	v_L

(*b*)

I	p_{I3}	p_{I4}
1	$V_S - D_{nS}C_S - V_L + D_{nL}C_L$	$V_S - V_L - f + c_0 + n(c_S - q_S R_S)$
2	$f - c_0 - nc_L + D_{nS}(R_S - C_S) + V_S - V_L + D_{nL}C_L$	$V_S - V_L$
3	0	$-f + c_0 + n(c_S - q_S R_S)$
4	$f - c_0 - nc_S + D_{nS}R_S$	0
5	$v_S - (1 - (1 - q_S)^n)C_S$	$v_S - f + c_0 + n(c_S - q_S R_S)$
6	$f - c_0 - nc_S + D_{nS}(R_S - C_S) + v_S$	v_S

(*c*)

I	p_{I5}	p_{I6}
1	$(1 - (1 - q_L)^n)C_L - v_L$	$-f + c_0 - v_L$
2	$f - c_0 + (1 - (1 - q_L)^n)C_L - v_L$	$-v_L$
3	$(1 - (1 - q_S)^n)C_S - v_S$	$-f + c_0 - v_S$
4	$f - c_0 + (1 - (1 - q_S)^n)C_S - v_S$	$-v_S$
5	0	$-f + c_0$
6	$f - c_0$	0

$$q_H > \max\left(\frac{V_H}{C_H}, \ \frac{c_H}{R_H}\right) \tag{16}$$

and

$$\textit{either } q_O > \frac{V_O}{C_O} \quad \textit{or} \quad v_O < 0. \tag{17}$$

Note that inequality (16) requires $V_L < C_L$ and $c_H < R_H$.

Otherwise, the stability of NM depends on group size: for NM to be stable, there is a critical value, say $n_{\text{crit}} + 1$, that $n + 1$ must exceed. Suppose, for example, that inequality (16) is satisfied and $V_O/C_O < 1$, but that inequalities (17) are false. Then the effect of B/V_O on inequality (13) is negligible (except to the extent of precluding inequality (17)), and so critical group size is well approximated by ensuring that $(1 - (1 - q_O)^{n_{\text{crit}}})C_O/V_O$ exceeds 1, which yields

Table 4. *Some critical group sizes when $q_O < V_O/C_O = 0.5$*

q_O	$n_{\text{crit}} + 1$	q_O	$n_{\text{crit}} + 1$
0.005	140	0.025	29
0.01	70	0.03	24
0.015	47	0.05	15
0.02	36	0.1	8

$$n_{\text{crit}} + 1 \approx \left[\frac{\ln(1 - V_O/C_O)}{\ln(1 - q_O)}\right] + 2, \tag{18}$$

where $[z]$ denotes the integer part of z. Table 4 shows some illustrative values for $V_O/C_O = 0.5$. The effect of group size is potentially significant.

4. IMPLICATIONS

In general, if a strategy is the only stable one, then it will ultimately emerge as the community norm; but if a second strategy is also stable, then the first will emerge only if it yields a higher community reward. Thus, for a conservation agreement to hold (when $v_H > 0$, as we have assumed), either the government must ensure that the no-poaching, monitoring strategy, NM, supporting the agreement is the unique stable strategy; or, if the strategy HX of poaching (with the higher value technology) and not monitoring is also stable, then the government must ensure both that NM is stable and that NM yields a higher community reward than HX. Now, in terms of the reward matrix **A** defined by table 2, strategy J yields a higher community reward when it yields a higher value of a_{JJ} (i.e. when it yields a higher reward to each individual if the whole population adopts it). So, because NM is the fifth strategy in table 1 whereas HX is either the second or fourth, if HX is stable then the government must ensure that $a_{55} > \max(a_{22}, a_{44})$ or, on using table 2, that

$$f - c_0 + \frac{B}{n+1} > V_H. \tag{19}$$

The higher the value of c_H, or the lower the value of R_H, the greater the significance of the above inequality. If the conservation strategy NM is the only stable one, then the relatively high value of R_H/c_H that guarantees inequality (14) will coerce the community into conserving the resource, and inequality (19) need not hold. If NM is stable but R_H/c_H is too small to destabilize the anti-conservation strategy HX, however, then the emergence of NM will require the community's voluntary cooperation, which can be induced by the government only if it pays a community benefit high enough to make NM yield a higher reward than HX; or, on rearranging inequality (19), if

$$B > (n + 1)(V_H - f + c_0). \tag{20}$$

Then $(n + 1)(V_H - f + c_0)$ is the minimum cost to the government of ensuring that NM has the higher reward. But it also costs the government f per individual, or

$(n+1)f$ in all, to render NM stable. Including this cost makes $(n+1)(V_H + c_0)$ the total minimum price tag for inducing conservation through community self-monitoring.

Suppose, however, that the government neglects to pay the community for monitoring *per se*. In other words, suppose that $f = 0$. Then although, by inequality (20), NM still yields a higher reward than HX, it is no longer a stable strategy, because $p_{65} = c_0$ is negative: if no one is poaching and no one is being paid to monitor, then it pays to switch to not monitoring, thus avoiding the opportunity cost c_0. But although NX would conserve the resource, it is not a stable strategy. From table 3*c*, to render it stable requires $v_H < 0$, or $B > (n+1)^2 V_H$: when $f = 0$, the minimum price tag for inducing conservation is raised to $(n+1)^2 V_H$. In other words, the minimum cost to the government of an effective community agreement to conserve the resource when $f = 0$ is greater than when $f > c_0$ by a factor $(n+1)V_H/(V_H + c_0)$. If c_0 is very much less than V_H, as suggested by inequalities (7), this factor is approximately $n+1$. We know of no community for which $n+1$ would be less than 10. We therefore conclude that an agreement among residents to conserve a wildlife resource through community self-monitoring may be cheaper by at least an order of magnitude for a government to sustain if its community incentive structure separates benefits for not poaching and bonuses for arrests made from payments for monitoring *per se*. Most community-based wildlife management schemes are expected to be self-sustaining in the long run, through income from activities such as legal hunting and safaris (Child 1996). In these terms, our analysis suggests that $f = 0$ makes the community's income much less likely to exceed the cost of its management regime, and hence to sustain the agreement.

Previous analyses have ignored the important distinction between the value of an agreement and its strategic stability (Child 1996; Gibson & Marks 1995): community benefits may strongly influence the former, yet have little influence on the latter. For example, if $B/(n+1)$ is very much greater than $f - c_0$, then the (individual) value of an agreement to adhere to NM, namely, $a_{55} = f - c_0 + B/(n+1)$, is dominated by the magnitude of B: $f - c_0$ has negligible influence on it. Nevertheless, as our analysis has clearly shown, the magnitude of B need have no effect on the stability of that agreement, whereas the effect of $f - c_0$ on the agreement's stability can never be ignored.

5. DISCUSSION

In this paper, under reasonable assumptions about relative economic magnitudes (see § 2), we have identified constraints for a community-based wildlife conservation programme to be sustainable. Relevant parameters (defined at length in § 2, but also listed for ease of reference in Appendix 1) include an opportunity cost c_0 and a fee f for monitoring; detection probabilities q_L and q_S for hunting with guns and snaring, respectively; and corresponding individual value/cost ratios V_L/C_L, V_S/C_S and technology-specific cost/reward ratios c_L/R_L, c_S/R_S for poaching and monitoring, respectively. Constraints on these parameters—in particular, that no agreement can be sustainable unless f is positive and exceeds c_0—are identified in § 3. Their implications for programme design are explored in § 4.

Wildlife conservation through community self-monitoring is an example of 'by-product mutualism' (Brown 1987), in which some cooperative behaviour—here, not poaching—is an incidental consequence of otherwise selfish behaviour. The mechanism that supports by-product mutualism is a sufficiently adverse environment, which requires a 'boomerang factor'—i.e. any factor that makes non-cooperators sufficiently likely to victimize themselves (Mesterton-Gibbons & Dugatkin 1992). Here, the boomerang factor is that intercepted poachers will be fined more than their kill is worth ($C_H > V_H$ being a constraint identified in § 3); and the environment is sufficiently adverse if monitoring is sufficiently effective, which depends on both the number of monitoring individuals and the detection probability for each.

Our analysis thus highlights a fundamental distinction between 'reciprocal altruism' (Axelrod & Hamilton 1981)—in which individuals keep score of pairwise interactions—and by-product mutualism as the basis for cooperative behaviour. For stable reciprocity among mobile individuals, there is always in principle an upper bound that group size must not exceed; although, if conditions are especially favourable for reciprocity, then this upper bound may lie at infinity, and hence be ignorable (Mesterton-Gibbons & Childress 1996). If, however, conditions for reciprocity are less favourable, then the upper bound is finite and potentially a major constraint, as suggested by Dwyer & Minnegal (1997, p. 105) in the context of sago flour production in a lowland Papua New Guinea community. For stable mutualism, on the other hand, there is always in principle a lower bound that group size $n+1$ must exceed. If conditions are especially favourable for mutualism, then the critical mass may lie at the lowest possible group size, namely 2, and hence be ignorable; but if conditions for mutualism are less favourable, then the lower bound is at least moderately large and again potentially a key constraint. In the present circumstances, conditions are especially favourable for mutualism only if the detection probabilities are large enough to satisfy both inequalities (16) and (17). Otherwise, the effect of the critical lower bound may be significant, as illustrated by table 4. Child (1996) has argued that, for a community-based project to work, the community should be small enough to meet under a tree, which he interprets as having no more than 200 households. Thus, table 4 suggests that the the range of sizes at which communities are effective may actually be quite narrow.

Gibson & Marks (1995) discuss in qualitative terms why the failure of community-based management programmes to address individual incentives leads to failure to achieve their objectives, in terms of controlling poaching by residents. Here we have shown how important it is to consider not only whether there are sufficient incentives for residents to stop poaching, but also whether there are sufficient incentives for them to continue monitoring. No self-monitoring agreement can be sustainable without a payment to each individual that exceeds the opportunity cost of monitoring—even if no one is poaching. Otherwise, it pays to switch to neither poaching nor monitoring, which is not a stable strategy.

Finally, potential shortcomings of our analysis include our assumptions that monitors would have useful work to be paid for even if no one were breaking the law, and that monitors would always report observed infractions. Nevertheless, with regard to the first, there is no reason in principle why residents on community-owned lands could not perform monitoring duties similar to those routinely delegated to scouts in the protected areas. For example, Marks (1994) shows how local hunters can participate in population surveys of game species, by recording information such as the time taken to encounter an individual of a particular species, and the area, time of day and season at which animals are encountered. Similarly, Leader-Williams *et al*. (1990) demonstrate how data on elephant and rhino population trends can be recorded by professional game scouts during their law enforcement activities. Scouts also routinely record information on signs of poaching activity, which can be used to estimate the general level of poaching activity in an area (Leader-Williams *et al*. 1990). With regard to the second potential shortcoming, if community monitors were organized into teams expected to complete such tasks, as happens with professional game scouts, then there would be fewer opportunities for individuals to cheat by receiving the fee f without actually monitoring. Moreover, a concern that monitors might not always report observed infractions translates into game theory as a concern that the strategy $\mathcal{NM}$ of not poaching and monitoring, although stable against each of the other five strategies in table 1, could perhaps be invaded by a seventh strategy of pretending to monitor and claiming the fee. All games, however, are subject to the rider that stability means stability with respect to a given strategy set (Mesterton-Gibbons 1992, p. 181). Conditions for $\mathcal{NM}$ also to be stable against other strategies could not be less stringent than those we have identified. Thus, even if, strictly, our conditions have limited validity as sufficient conditions, as necessary conditions their validity is broad.

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APPENDIX A: LIST OF SYMBOLS

a_{IJ}: the reward to an individual using strategy I against n individuals using strategy J.

B: maximum community benefit per period for conserving resource.

C_Z: expected cost per period of a conviction for type-Z poaching.

c_0: opportunity cost of monitoring.

c_Z: marginal disutility of social opprobrium for monitoring type-Z hunters.

D_{iZ}: probability of being detected using type-Z technology when i individuals monitor; see equation (3).

f: fee paid to individuals for monitoring.

H: Used to denote L (see below) if $V_L > V_S$ but S if $V_S > V_L$ (H stands for higher value).

i: number of individuals monitoring.

j: number of other individuals engaged in type-L poaching.

k: number of other individuals engaged in type-S poaching.

L: used as a subscript to denote hunting with guns (L stands for long-range technology). Also used to define strategies in table 1.

L_i: expected benefit per period to each individual poaching with type-L technology when i individuals are monitoring (used with both $i=0$ and $i=n$ in table 2).

M: used to denote monitoring in defining strategies; see table 1.

M_i^{jk}: expected benefit per period to each monitoring individual, where i, j and k are defined above; see equation (8).

N: used for not poaching in defining strategies; see table 1.

$n+1$: size of community (number of decision-making families or individuals).

O: used to denote L (see above) if $V_L < V_S$ but S if $V_L > V_S$ (O stands for other than higher value—we cannot use L for lower because L is already in use for long-range).

p_{IJ}: the element in row I and column J of the stability matrix; see equation (9).

q_Z: probability per period that a monitor is observing while type-Z technology is used.

R_Z: bonus paid by the government to the first informant of a type-Z infraction.

S: used as a subscript to denote hunting with snares (short-range technology). Also used to define strategies in table 1.

S_i: expected benefit per period to each individual poaching with type-S technology when i individuals are monitoring (used with both $i=0$ and $i=n$ in table 2).

V_Z: expected value of returns per period from poaching with type-Z technology.

v_Z: net expected value per period from using type-Z technology; see equation (5).

W_m: community 'wage' to each individual when m individuals are poaching; see equation (1).

X: used for not monitoring in defining strategies; see table 1.

Z: generic subscript to denote any of H, L, O or S (see above).

Z_i: expected benefit per period to each individual poaching with type-Z technology when i individuals are monitoring; see equation (2).