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Abstract

This paper analyses the economics of pest and nuisance relating to wild animals. It studies stylised models where wild animals represent a direct nuisance to agricultural production through grazing and crop damage. Such damage is particularly relevant in poor rural communities, where people are dependent on livestock and crop production and at the same time are living close to nature and wildlife. The analysis encompasses both situations involving nuisance costs only and cases where the wildlife may also have a harvesting value. In both instances, the emphasis is on large mammals and criteria for optimal species eradication are analysed in particular.

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1. Introduction

In many cases, wild animals are of benefit to humans. Quite frequently, however, we also find that wild species are a nuisance. This is often the case in poor rural communities where

people are dependent on livestock and crop production and at the same time are living close to wildlife and nuisance species. The agricultural damage may take place in a variety of ways, including eating crops and pastures; preying on livestock; rooting; tramping; pushing away obstructions such as fences; wallowing; and acting as carriers of weeds, parasites and diseases (Hone 1994).

The control of agricultural pests such as insects, mites and weeds has been the main focus of literature in this field (Carlson and Wetzenstein 1993 provides an overview), whereas analyses of the damage caused by large mammals are relatively few in number. Tisdell (1982) provides a detailed study of the damage and control costs relating to feral pigs in Australia. In addition, the cost and benefits of feral pigs causing damage on Californian range-land has been studied by Zivin *et al.* (2000) using a bio-economic model and optimal control. The management of an African elephant population causing grazing damage, but at the same time representing consumptive as well as non-consumptive values, is analysed within the same framework by Horan and Bulte (2004). Among others, Kiss (1990) and Swanson and Barbier (1992) give descriptive overviews. For a more recent overview, see Graham *et al.* (2005).

The present analysis follows up these studies of nuisance and damage caused by large wild animals in a developing country setting where a stylized and traditional bio-economic modelling approach is used. The basic questions analysed are how to define a nature stock as an ‘economic nuisance’; to what extent it is economically reasonable to harvest from a nuisance stock; and when it is optimal to exterminate the nuisance. A classic analysis of the bioeconomics of extermination is Clark (1990) while Schulz (1996) discusses the economics of the extermination of terrestrial animal species. See also Swanson (1994). Our analysis builds to some extent on Zivin *et al.* (2000), but the conditions for extermination or for living with the nuisance are discussed in a more fundamental way. Hence, contrary to their analysis, the possibilities of extermination or of not trapping at all are studied both by looking at the conditions when an internal optimal solution approaches the boundaries of zero and the carrying capacity, and by comparing the present-value profit of the programmes of an interior solution with that of these boundary solutions. These present-value comparisons are the main contribution of this paper. In Section 2 we analyse first the pure nuisance case, with no benefits related to the wild species. As a next step, in Section 3, an income stream of the wildlife when harvested, or cropped, is introduced. This case is analysed first without harvesting costs and then with costs added. We are presuming throughout that management is

taking place at a farm level, or village level, with no positive non-consumptive value (e.g. existence value) of the species included. The present notion of ‘optimal extermination’ therefore has a clearly restricted meaning.

2. No value to the wild species, just nuisance

2.1 The model

Like Zivin *et al.* (2000), we consider a landowner operating a piece of land with $A > 0$ as the crop profit in the absence of damage. A population of wild animals X (measured in number of individuals) at time t (the time notation is omitted) is eating up, or damaging, the yield. The damage is given by $N = N(X)$, with $N(0) = 0$ and $\partial N / \partial X = N_X > 0$. When normalizing the damages to the crop profit (see e.g. Carlson and Wetzstein 1993), the net agricultural profit reads

$$(1) \quad U = A(1 - N(X)) \geq 0.$$

The cost of controlling the nuisance depends on the number of trapped (or harvested) animals h and the stock size. The cost function is formulated as

$$(2) \quad C = c(X)h.$$

The cost is therefore assumed to be linear in the harvesting, while the unit trapping cost $c(X) > 0$ decreases in the stock abundance as trapping becomes progressively more difficult as the animal population becomes small, $c_X < 0$. In addition, we have $c_{XX} > 0$.

The population grows according to the density dependent natural growth function $F(X)$:

$$(3) \quad \frac{dX}{dt} = F(X) - h$$

Throughout, we are considering the natural growth function as a logistic-type model with $F(0) = F(K) = 0$, where $K > 0$ is the carrying capacity and $F_{XX} < 0$, and where F_X is positive for a stock size below that of X^{msy} and negative when $X > X^{msy}$.

When the species has no harvesting value, the management problem is to balance the crop benefit (decreasing with the species abundance) with the control costs (increasing with the number of species removed). The optimization problem is thus to maximize the present-value net benefit

$$(4) \quad PV = \int_0^{\infty} [A(1 - N(X)) - c(X)h] e^{-\delta t} dt$$

under the constraint (3) and $X(0)$ given, and where $\delta > 0$ is the discount rate, i.e. the return on alternative capital assets.¹

We start by solving the model when assuming an interior solution. Next, we consider extermination, and living with nuisance in its starkest form, i.e. keeping the wildlife at its carrying capacity in the long term.

2.2. Controlling the nuisance, but living with it

The current-value Hamiltonian of the above problem is

$$H = A(1 - N(X)) - c(X)h + \lambda(F(X) - h), \text{ where } \lambda \text{ is the shadow price of the wild animals.}$$

When we have an interior solution, i.e. a positive stock size, and harvesting taking place at the steady state, the first order conditions for maximum are

$$(5) \quad -c(X) - \lambda = 0$$

and

$$(6) \quad \frac{d\lambda}{dt} = \lambda\delta + AN_x(X) + c_x(X)h - \lambda F_x(X).$$

Equation (5) states clearly that when only a nuisance, the shadow price of the animals will be negative.

¹ In the present problem A is fixed, and hence there is no trade-off between effort use in crop production and trapping (see e.g. Schulz and Skonhofs 1996). The present problem is equivalent to the problem of minimizing the present-value cost $\int_0^{\infty} [AN(X) + c(X)h] e^{-\delta t} dt$.

When combining the first order conditions and using the natural growth function (3), we obtain the reduced form first order condition as

$$(7) \quad \delta = \frac{AN_X(X^*) + c_X(X^*)F(X^*) + c(X^*)F_X(X^*)}{c(X^*)}$$

which determines the steady-state equilibrium stock X^* . In the next step, the number of animals trapped follows from equation (3) when $dX/dt = 0$, $h^* = F(X^*)$. Thus, equations (7) and (3) represent a singular system because the Hamiltonian is linear in h . The above control problem is therefore of the ‘bang-bang’ type, and the transitional dynamics must obey a *MRAP*-strategy (*Most Rapid Approach Path*).

It is obvious that an optimal managed stock will never be larger if a nuisance effect is linked to it than without this effect: wild animals without value will be left uncontrolled if they have no negative influence on crop production. When controlled, however, equation (7) states that the opportunity cost of capital should be equal to the marginal natural growth plus the marginal stock effects. Two marginal stock effects are present, the cost effect $c_X(X^*)F(X^*) + c(X^*)F_X(X^*)$ and the marginal damage effect $AN_X(X^*)$. The cost effect depends on the marginal unit control term $c_X(X^*)$ and if its absolute value is large, it is optimal to have a small number of animals, $(\delta - F_X(X^*)) < 0$. This is sustained because the trapping cost decreases, while the damage cost increases with the number of animals.

By introducing shift factors for the cost and damage functions, and taking into account the total differential of equation (7), it may be confirmed that more nuisance as well as a more valuable crop means a smaller stock. A higher harvesting cost, on the other hand, means more animals. These effects may seem to contrast with the above condition for a small steady-state stock when the marginal control effect dominates the marginal nuisance effect, i.e.

$(\delta - F_X(X^*)) < 0$. However, the marginal trapping cost can only be large for a small stock size. The effect $\partial X^* / \partial \delta > 0$ differs from the standard harvesting model (see e.g. Clark 1990), and the reason is that there is no direct benefit from harvesting in the present model. Indeed,

the situation is the opposite, as effort must be made to keep the stock small and the opportunity cost for this effort increases with a higher rate of discount.

The solution (7) may be illustrated using the standard Gordon-Schäfer approach. The natural growth function then reads $F(X) = rX(1 - X/K)$, where $K > 0$ (as mentioned) is the carrying capacity, $r > 0$ is the maximum specific growth rate, and the unit trapping cost function is specified as $c(X) = a/X$ with $a > 0$. When assuming a linear damage function $N(X) = \alpha X$ with $\alpha > 0$, the model has the same specifications as Zivin *et al.* (2000). Given these functional forms, the *RHS* of equation (7) yields $(1/a)(\alpha A - ra/K)X$. To obtain an interior solution, the *RHS* as well as the *LHS* of (7), i.e. the rate of discount, must therefore be positive. Under these conditions the steady-state stock reads² $X^* = \delta a / (\alpha A - ra/K) > 0$. Because αA yields the marginal stock damage cost, while $(-ra/K)$ gives the marginal trapping cost, an interior solution is therefore characterized by marginal damage dominance. X^* approaches zero when the rate of discount becomes small. If, on the other hand, the unit trapping cost is large and the marginal damage is low, it may be optimal to keep the species uncontrolled. We shall now analyse these boundary solutions more closely.

2.3. Extermination of the nuisance, or leaving it unexploited

Clark (1990, Section 2.8) analyses the economic and ecological conditions leading to extinction in the standard harvesting model. Using a purely compensatory natural growth function (as here), he finds that extinction is optimal if the harvesting price is higher than the (constant) unit harvesting cost when the stock size is close to zero, and if the rate of discount is substantially higher than (twice as high as) that of the maximum specific growth rate of the species.

Clark analyses a nature asset stock, which will be left unexploited for a negative harvesting profit. Our case is opposite. We analyse a nuisance species where the stock is a *liability* to the manager, and we study the conditions for the steady-state stock to approach $X^* = 0$ when initially assuming a positive stock. To find the more precise conditions for extinction being an optimal policy, however, this possibility should be viewed from two different angles:

- (i) looking at the conditions for X^* approaching zero when initially having $0 < X^* < K$, or
- (ii) comparing the present-value profit of driving the species to extinction with that of keeping

² Zivin *et al.* (2000) incorrectly states this condition as $X^* = \delta a / (\alpha A - ra/K)$

a positive stock size. As the management goal is present-value profit maximizing, the latter evaluation method dominates the former (further details below).

Not living with the nuisance at all and making the species extinct is optimal if the net discounted profit from doing so exceeds the net discounted profit from the internal optimal solution characterized by equation (7). When assuming that extermination takes place immediately, and hence neglecting the extinction time (but see below), the present-value

profit of no species left is $PV^{**} = \int_0^{\infty} [A(1 - N(\bar{X}))]e^{-\delta t} dt - W(X^0, \bar{X}) = A/\delta - W(X^0, \bar{X})$.

$W(X^0, \bar{X}) > 0$ is the extermination cost function, generally dependent on the initial stock X^0 and the stock size \bar{X} determining extinction. When X is measured by the number of individuals (as here), \bar{X} is conventionally set to one (see e.g. Lande *et al.* 2003, Ch. 2).

On the other hand, for an internal solution $0 < X^* < K$, the present-value profit reads

$$PV^* = \int_0^{\infty} [A(1 - N(X^*)) - c(X^*)F(X^*)]e^{-\delta t} dt - W(X^0, X^*)$$

$$= (1/\delta)[A(1 - N(X^*)) - c(X^*)F(X^*)] - W(X^0, X^*)$$
 when still assuming the steady state to be approached immediately (zero *MRAP*-time) and where $W(X^0, X^*) \geq 0$, as above, represents the cost of reaching the steady state. $W(X^0, X^*) = 0$ if $X^0 < X^*$, otherwise it is positive. The difference between these two harvesting programmes is accordingly

$$PV^{**} - PV^* = (1/\delta)[AN(X^*) + c(X^*)F(X^*)] + W(X^0, X^*) - W(X^0, \bar{X}).$$

As $W(X^0, \bar{X}) > W(X^0, X^*)$ always holds, extermination is optimal either if this difference is small combined with a modest present-value cost of the nuisance stock, or if the present-value cost of the nuisance stock $(1/\delta)[AN(X^*) + c(X^*)F(X^*)]$ is large. This may happen when δ is small, or when the current cost is high. Hence, under these conditions, equation (7) with $X^* > 0$ does not represent the optimal solution. This is a far more general conclusion than Zivin *et al.* (2000) and is stated as

Result 1: *Extermination of a pure nuisance species is optimal if the cost of extermination is small. Extermination is also optimal if the nuisance cost and/or the control cost is high for a positive internal solution.*

When, like Zivin *et al.*, we use the linear damage function combined with the Gordon-Schäfer assumptions, it is possible to draw a somewhat more definitive conclusion. We then find

$$PV^* = (1/\delta)[A - a(r + \delta)] - W(X^0, X^*) \text{ when inserting for } X^* = \delta a / (\alpha A - ra / K) \text{ (see above).}$$

The present-value profit difference becomes now

$$PV^{**} - PV^* = (a/\delta)(r + \delta) + W(X^0, X^*) - W(X^0, \bar{X}). \text{ On the assumption of zero extermination time, the extermination cost function reads}$$

$$W(X^0, \bar{X}) = \int_{\bar{X}}^{X^0} c(X) dX = \int_{\bar{X}}^{X^0} (a/X) dX = a \ln X^0 \text{ when } \bar{X} = 1 \text{ (see above). If the initial stock is}$$

above that of the interior steady state, $X^0 > X^*$, we find in the same manner

$$W(X^0, X^*) = a \ln(X^0 / X^*). \text{ The present-value profit difference}$$

$PV^{**} - PV^* = (a/\delta)(r + \delta) - a \ln X^*$ is positive when $(1/\delta)(r + \delta) - \ln X^* > 0$.³ When inserting for X^* , $PV^{**} - PV^* > 0$ implies $(1/\delta)(r + \delta) - \ln[\delta a / (\alpha A - ra / K)] > 0$. In contrast to Zivin *et al.*, we can therefore conclude that extermination may be optimal for a positive rate of discount. This is stated as

Result 2: *Using the Gordon-Schaefer assumptions combined with a linear damage function, extermination may be optimal for a positive rate of discount.*

Table 1 demonstrates this result with a numerical example. It is seen that $PV^{**} - PV^* > 0$ for a discount rate up to about 10 %. However, as has already been made clear, these calculations build on the assumption that the steady states are approached immediately. The realism of reaching the steady state immediately may be questioned. Amongst other things, it requires a large trapping capacity, and the time used for eradication leads to some additional nuisance costs. On the other hand, the present-value trapping costs will be somewhat reduced due to discounting. However, such additional extermination costs need to be quite significant to change the qualitative content of the calculations in the table.

Table 1 about here

To complete the analysis, the profitability of the other extreme solution (not trapping at all and living with the nuisance in its starkest form) must also be found. Starting from $X^0 = K$,

³ When starting with $X^0 < X^*$, $\ln X^0$ replaces $\ln X^*$ in this present-value profit difference.

the present-value profit of keeping the stock uncontrolled is

$$PV^{***} = \int_0^{\infty} A(1 - N(K))e^{-\delta t} dt = (1/\delta)A(1 - N(K)).$$

When, as an initial stage, the cost of reaching the steady state $W(K, X^*)$ in the internal solution is neglected, the present-value profit difference is $PV^{***} - PV^* = (1/\delta)[c(X^*)F(X^*) - A(N(K) - N(X^*))]$. Using the linear damage function together with the Gordon-Schäfer approach, this reads

$PV^{***} - PV^* = a(1/\delta)[(r + \delta) - \alpha AK/a]$. When keeping the species controlled in the internal local optimal solution, the stock is $X^* > 0$ together with $X^* = \delta a / (\alpha A - ra/K) \leq K$. The last inequality may also be written as $(r + \delta) - \alpha AK/a \leq 0$. It is thus seen that

$PV^{***} - PV^* = 0$ when $X^* = K$ and $PV^{***} - PV^* < 0$ when $X^* < K$. Hence, in the Gordon-Schäfer case, starting with $X^0 = K$ and neglecting the cost of reaching the steady state, the condition for keeping the stock uncontrolled is equal to the condition for $X^* = K$ in the internal solution. However, two factors work in the direction of increasing the present-value difference $PV^{***} - PV^*$. Firstly, we have the cost of reaching the internal steady state. Secondly, if $X^0 < K$, the nuisance cost of the option of keeping the species uncontrolled reduces over a time interval until the stock reaches K . We can therefore state

Result 3: *Keeping the stock uncontrolled may be the best solution, even if there exists a local internal optimal solution $X^* < K$.*

In Table 1 we have also included a calculation for PV^{***} . Because we are starting with $X^0 = K$, this example confirms that we have $PV^{***} - PV^* < 0$ for all $X^* < K$.

2.4. Other control measures

The pure nuisance model may be extended along different lines reflecting other types of nuisance control. One obvious way is to introduce a control measure that influences the fertility and hence the natural growth of the wild animals (see e.g. Levhari and Withagen 1992).⁴ When V is the control measure affecting natural growth at a cost of q per unit, and hence $F(X, V)$ replaces $F(X)$ with $F_V < 0$, the present value reads

⁴ Influencing the natural growth function may also be interpreted as if selective trapping takes place.

$$(8) \quad PV = \int_0^{\infty} [A(1 - N(X)) - c(X)h - qV] e^{-\delta t} dt$$

when we also have trapping. The Hamiltonian is now $H = A(1 - N(X)) - c(X)h - qV + \lambda(F(X, V) - h)$. When it is profitable to trap but not exterminate the species, and use the new control measure as well, $V^* > 0$, the first order conditions for maximum are $-q + \lambda F_V(X, V) = 0$ together with (5) and (6), except that $F_X(X, V)$ replaces $F_X(X)$ in (6). The reduced form steady-state conditions are therefore now

$$(9) \quad \delta = \frac{AN_X(X^*) + c_X(X^*)F(X^*, V^*) + c(X^*)F_X(X^*, V^*)}{c(X^*)}$$

and

$$(10) \quad -\frac{q}{F_V(X^*, V^*)} = c(X^*)$$

in addition to $h^* = F(X^*, V^*)$. Condition (10) simply states that the marginal cost of using the new control measure should be equal to the marginal trapping cost.⁵

When the new control measure is profitable to use, the present-value profit is obviously higher than without it. The suspected result of a smaller pest stock when having an additional control available is not, however, necessarily present. Hence, when taking the total differential of equation (9), we find that the condition for a smaller stock size when using the new control is $c_X(X^*)F(X^*, V^*) + c(X^*)F_{XV}(X^*, V^*) > 0$. Only when $F_{XV}(X^*, V^*) \geq 0$ is the nuisance stock therefore unambiguously smaller through having the additional control measure. The comparative statics in the extended model are the same as in the basic model analysed above. Only a new controlling measure has been added, and we find a trade-off in the cost of the two controlling measures, as demonstrated in equation (10). In addition, $\partial X^* / \partial q > 0$ holds.

⁵ The dynamics of this control problem is also of the ‘bang-bang’ type for the control h . The dynamic path of V adjusts accordingly through equation (10).

Result 4: *A situation where the nuisance species is controlled by influencing its natural growth may be analysed in a similar way to a case of control by trapping.*

3. The nuisance also represents a value

3.1 No harvesting costs

In the above analysis, wild animals represent only nuisance. However, in many instances animals, when removed, also yield a value in the form of meat, or trophies. This is often true of elephants and other large mammals (cf. Introduction). When wild animals have a hunting value, the management problem is to balance the crop benefit, decreasing the size of the wild species, and the control benefit, increasing the number of animals hunted. Consequently, when hunting permits are sold at the price $p > 0$, assumed to be fixed and independent of the offtake and size of the population, the problem is to maximize

$$(11) \quad PV = \int_0^{\infty} [A(1 - N(X)) + ph]e^{-\delta t} dt$$

subject to the constraint $dX / dt = F(X) - h$.

The first order conditions are $p - \lambda = 0$ and $d\lambda / dt = \lambda\delta + AN_X(X) - \lambda F_X(X)$ when there is an interior solution. The shadow price is therefore now positive, irrespective of the fact that the wild species also represents a nuisance.⁶

The reduced form long-term equilibrium condition yields

$$(12) \quad \delta = \frac{-AN_X(X^*) + pF_X(X^*)}{p}.$$

⁶ Assuming the harvesting price to be unaffected by the number of animals harvested and that the size of the stock is clearly unrealistic in some instances. If the price depends on the number of animals removed and we have $p = p(h)$ with $p_h < 0$, the control condition reads $p(1 + p_h h / p) = \lambda$. Hence, the shadow price may, depending on the size of the demand elasticity, be negative. If so, the optimal nuisance may be at a point where $(\delta - F(X^*)) > 0$ holds (see main text). This case is considered in Zivin *et al.* (2000). When a higher stock density makes harvesting more valuable, we also have $p = p(h, X)$ with $p_X > 0$.

The location of X^* will now always be at a point characterized by $(\delta - F_x(X^*)) < 0$, determined by the size of the marginal nuisance *relative* to the harvesting price, and the stock will be smaller compared to a situation without any nuisance. It is hence always optimal to remove animals and the stock will never be left unexploited. This result may also be confirmed by calculating the present-value profit. When the time taken to reach the steady state is now also ignored, we find $PV^* = (1/\delta)[A(1 - N(X^*)) + pF(X^*)] + p(X^0 - X^*)$, where the last term replaces the previous extermination cost function and represents the immediate harvesting value *gain* of reaching the steady state (when still starting with $X^0 > X^*$). Compared with keeping the stock uncontrolled, the difference is now

$PV^{**} - PV^* = -(1/\delta)[A(N(K) - N(X^*)) + pF(X^*)] - p(X^0 - X^*) < 0$. This result is obvious as harvesting now represents profit, and at the same time reduces the nuisance cost. This is stated as

Result 5: *A nuisance stock with a harvesting value but no controlling cost will never be left unexploited.*

While the stock will never be left unexploited, it may, as in the pure nuisance model, be optimal to exterminate it. From condition (12) it is evident that a low harvesting price works in the direction of a low X^* , and this is the opposite result of the traditional Clark (1990) model. A valuable crop, together with high marginal damage, works in the same direction. As in the pure nuisance model, however, extinction may represent the overall optimal policy even if X^* is positive. The present value of extinction is now $PV^{**} = A/\delta + p(X^0 - \bar{X})$, when again neglecting the extinction time, and

$$PV^{**} - PV^* = (1/\delta)[AN(X^*) - pF(X^*)] + p(X^* - \bar{X}).$$

When again using the Gordon-Schäfer model combined with the linear damage function, we find $X^* = (K/2pr)[(r - \delta)p - \alpha A]$, i.e. $X^* = 0$ if $\alpha A > (r - \delta)p$. Inserting for X^* , the present-value profit difference reads $PV^{**} - PV^* = (X^*/2\delta)[\alpha A - (r - \delta)p] - p\bar{X}$ after some small rearrangements. Ignoring the (very small) income term $p\bar{X}$, the condition for extinction is therefore the same, achieved either by evaluating the present-value profit difference or by finding the condition for X^* approaching zero.

Result 6: *Extermination of a nuisance stock with a harvesting value but no control cost is always optimal if the current nuisance cost exceeds the current harvesting value in the internal optimal solution. In the Gordon-Schäfer case, the conditions of extinction may be found by examining when the optimal internal stock approaches zero.*

3.2 Harvesting costs

The present case, with a species value, may be analysed somewhat more generally when harvesting costs are also included. The net hunting benefit is then

$$(13) \quad B = [p - c(X)]h = b(X)h$$

with $b(X)$ as the unit profit, increasing in the stock size, $b_X = -c_X > 0$. Observe that having $b_X > 0$ may also be interpreted as a situation where increased stock makes the hunting permits more valuable for larger stocks. Contrary to the standard harvesting problem (with no nuisance), $b(X)$ can be either positive or negative. The two models above are therefore nested by this one, with the pure nuisance case as $b(X) = -c(X) < 0$ and the value case as $b(X) = p > 0$.

The present value benefit reads

$$(14) \quad PV = \int_0^{\infty} [A(1 - N(X)) + b(X)h]e^{-\delta t} dt,$$

with first order conditions $b(X) - \lambda = 0$ and $d\lambda/dt = \lambda\delta + AN_X(X) - b_X(X)h - \lambda F_X(X)$ when an interior solution is present. The shadow price may therefore now be positive or negative, depending on the stock size and unit harvesting cost, and hence the wild animals may be either a value or a nuisance.

The reduced form steady-state equilibrium follows as

$$(15) \quad \delta = \frac{-AN_X(X^*) + b_X(X^*)F(X^*) + b(X^*)F_X(X^*)}{b(X^*)}.$$

The location of X^* is more complicated than above and, depending on the cost and benefit structure, there are several possibilities. When the marginal harvesting benefit $b(X^*)$ is positive, $(\delta - F_X(X^*)) > 0$ holds when the cost term $b_X(X^*)F(X^*)$ dominates the nuisance term $AN_X(X^*)$. Hence, this will be an outcome when it is optimal to keep a large stock size. On the other hand, we have $(\delta - F_X(X^*)) < 0$ and few animals when the shadow price is positive and the nuisance term dominates. This is the opposite of the situation analysed above without harvesting benefit. However, when the marginal cost effect exceeds the harvesting price and we have $b(X^*) < 0$, the location of the equilibrium stock size, depending on cost or nuisance dominance, will be as in section 2.2 (see also Horan and Bulte 2004).

By differentiating condition (15), we find that the comparative static effects of the crop value and the harvesting and damage costs will be just as in the pure nuisance model. However, the price effect depends on the location of X^* , and $\partial X^* / \partial p > 0$ holds when the harvesting profit $b(X^*)$ is positive; the nuisance term dominates the cost term and it is a small stock size, $(\delta - F_X(X^*)) < 0$. On the other hand, for a negative harvesting profit and a dominating nuisance term, we find $\partial X^* / \partial p < 0$ and a higher price make it less costly to deplete a non-valuable stock. When $b(X^*) < 0$ the stock is again a net liability, and effort must be used to keep the stock small and $\partial X^* / \partial \delta > 0$. When, on the other hand, $b(X^*) > 0$, we have the standard result of $\partial X^* / \partial \delta < 0$.

It may offer additional insight to illustrate this solution by using the Gordon-Schäfer approach combined with the linear damage function $N(X) = \alpha X$. The steady-state stock then yields

$$X^* = \frac{[ra/K - \alpha A + (r - \delta)p] + \sqrt{[ra/K - \alpha A + (r - \delta)p]^2 + 8rpa\delta/K}}{4rp/K}. \text{ There must be}$$

restrictions on the damage cost and the value of the crop to obtain an interior solution in this model as well. Moreover, the unit trapping cost must be neither too small nor too large.

Again, these conditions become apparent by finding the conditions for approaching $X^* = 0$ and $X^* = K$, respectively, when initially assuming an interior solution.

However, just as in the previous models, the present value of the various programmes has to be compared, in order to find more precise conditions for the optimal strategies. Using the same assumptions as above, we now find

$$PV^* = (1/\delta)[A(1 - N(X^*)) + b(X^*)F(X^*)] + p(X^0 - X^*) - W(X^0, X^*) \text{ and}$$

$$PV^{**} = A/\delta + p(X^0 - \bar{X}) - W(X^0, \bar{X}). \text{ The difference reads}$$

$PV^{**} - PV^* = (1/\delta)[AN(X^*) - b(X^*)F(X^*)] + p(X^* - \bar{X}) + W(X^0, X^*) - W(X^0, \bar{X})$. If the shadow price is negative and $b(X^*) < 0$, we therefore obtain more or less the same result as in the pure nuisance case. This is stated as

Result 7: *Extermination of a valuable species with a negative shadow price is optimal if the cost of extermination is small.*

4. Concluding remarks

We have studied three different models of ecological nuisance. The analysis has been at a farm or village level, in a developing country setting, based on a large wild mammal species causing agricultural crop damage. Our analysis demonstrates that a nuisance resource will be managed quite differently from a valuable resource. Firstly, it is obvious that the farmers will deplete the nuisance stock compared to a situation where there is no crop damage. Secondly, the stock will be left unexploited only if the damage effect is small and if harvesting yields a negative profit. Thirdly, at a farm or village level it may very well make sense to eradicate the nuisance species. Two main problems have been highlighted. Firstly, the nature of a nuisance species as a nature liability has been discussed. Secondly, a nuisance species needs to be eradicated because of its effect on agriculture, and we specify the criteria for this decision.

However, as the present management problem is analysed at a farm (or village) level, the present notion of optimal extinction should be interpreted with care, and values reflecting existence value, or biodiversity, should be included from a *social* point of view. Extinction, or small and threatened stock sizes, will then rarely represent an optimal social solution. This gives room for introducing policy measures to increase the wildlife stock due to its social

value. Moreover, to safeguard a small nuisance stock from extinction, it should always be ensured that wild animals have a net *value* at a farm or village level.

The value of crop production is also important for the management of the nuisance, since the economic damage of the nuisance stock increases when agriculture becomes more profitable. Hence, policies of making agricultural production more profitable will never increase the number of wild animals. This supports the conclusions from Schulz and Skonhoft (1996) analysing the conflicting land-use for agricultural production and habitat purposes.

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Table 1. Pure nuisance model. Stock size internal solution X^* , present-value profit internal solution PV^* , present-value profit extermination PV^{**} and present-value profit no control PV^{***}

δ	0.01	0.05	0.09	0.13	0.17	0.20
X^*	5	25	45	65	85	100
PV^*	66.0	11.6	6.0	4.0	3.0	2.5
PV^{**}	95.4	15.4	6.5	3.0	1.3	0.4
PV^{***}	50.0	10.0	5.6	3.9	2.9	2.5

Table note. Parameter values: $K=100$, $r=0.3$. $A=1$, $a=1$, $\alpha=0.005$. Initial stock size: $X^0 = K = 100$