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On the Economics of Ecological Nuisance

by

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Abstract
The paper analyses the economics of pest and nuisance related to wild animals. We study stylised models where wild animals represent a direct nuisance for agricultural production through grazing and crop damages. These damages are particularly relevant in poor rural communities in third world countries where people are depending on livestock and crop production, and at the same time are living close to the nature and wildlife. The analysis includes both situations with only nuisance costs, and the case when the wildlife also can have a harvesting value. The emphasis is all the time on large mammals and the criteria for optimal species eradication are particularly analysed.

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Abstract

The paper analyses the economics of pest and nuisance related to wild animals. We study stylised models where wild animals represent a direct nuisance for agricultural production through grazing and crop damages. These damages are particularly relevant in poor rural communities in third world countries where people are depending on livestock and crop production, and at the same time are living close to the nature and wildlife. The analysis includes both situations with only nuisance costs, and the case when the wildlife also can have a harvesting value. The emphasis is all the time on large mammals and the criteria for optimal species eradication are particularly analysed.

1. Introduction

Wild species represent in most instances benefits for the humans. This is particularly so for various fish stocks which make up a large part of the diet of the world's population. The traditional way of analysing wild animals in an economic context is therefore to treat them as economic goods, and that utilisation through harvesting yields a net benefit. However, quite frequently we also find that wild animals represent a nuisance for people. This is often so in poor rural communities where people are depending on livestock and crop production, and where they at the same time are living close to wildlife and wild species. But also in developed countries wild mammals can frequently represent a nuisance. The agricultural damages takes place in a variety of ways. It includes eating crops and pastures, predation on livestock, rooting, tramping, pushing away obstructions such as fences, wallowing and acting as carriers of weeds, parasites and diseases (Hone 1994). Many local communities in African countries, as well as in other developing countries, therefore see large mammals basically as a nuisance (see, e.g., Kiss 1990 and Swanson and Barbier 1992, Swanson 1994)[1].

The root of most of these conflicts between humans and wild mammals lies in the *direct* competing uses of land, and expanding agriculture has all over the world depleted or exterminated wild species both to incorporate more land, and to secure agricultural benefits from damage of wild stocks (Kiss 1990). But the economics of ecological nuisance is not related only to terrestrial animal species and the competing uses of land. Marine species can also cause damages, not only benefits. As humans interact with marine species basically through harvesting (and pollution), however, the nuisance problem here will in most instances be of the *indirect* type where invaluable species (from a commercial point of view) prey upon, or compete with, valuable species (see, e.g., Flaaten and Stollery 1996). As already indicated**,** this kind of indirect impact can also be of some importance for terrestrial species as wildlife can predate upon livestock, and it can be grazing competition between livestock and wildlife. In terrestrial ecosystems species like wolves and other large predators will rarely be harvested for profit, but the stocks may be culled to keep the ecosystem in shape and allow for increased growth of other, valuable stocks (Wright 1999).

[1] There are few damage cost estimates caused by large mammals. One estimate is provided by Bulte and van Kooten(1999) who assume an yearly opportunity cost of an African elephant to be in the amount of bringing 4.7 cows to full maturity. Zivin *et al.*(2000) assume that an additional feral pig damages 6% of the rangeland crop value. Hone(1994) provides also some estimates of predation on livestock, and the costs of infectious diseases.

Most of the economics of pest control has been related to problems of controlling agricultural pests as insects, mites and weeds. See Carlson and Wetzenstein (1993) for a fairly recent overview. Only a small fraction of the papers reviewed here are studying vertebrate pest control problems with particular emphasis on mammals. However, there are some few works that fall within the domain of bio-economic analysis. Hone (1994) summarises a number of simple static pest control models, and presents some estimates of rodent damages as well as damages related to other mammals (cf. also footnote 1). Tisdell (1982) provides a very detailed study of the damages and control costs of feral pigs in an Australian context. The cost and benefit of feral pig, causing damages on Californian rangeland, is also studied in a recent paper by Zivin *et al*. (2000) within an optimal control framework. The management of elephants causing grazing damages, but at the same time also represents consumptive as well as non-consumptive values in an east-African context, is analysed within the same framework by Bulte and van Kooten (1998). Large mammals causing damages on agriculture production is also modelled by Schulz and Skonhoft (1996) and Skonhoft and Solstad(1998), but only as a side effect. The following analysis builds to some extent on Zivin *et al.* (2000), but the conditions for extermination or living with the nuisance are discussed in a more fundamental way. Hence, contrary to their analysis, the possibilities of extermination and 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 programs of an interior solution with that of these boundary solutions. For some species extermination seems to be unrealistic - usually due to high costs. However, the threat of species extermination is not a theoretical one. This is a major concern for most of the conservationist NGO's - focussing on species extinction in general, and specifically on large mammals. There have even been established huge international institutions, like the CITES, to protect endangered species. The threat of extinction is an economic one, and this paper will focus on the economic conditions that makes extermination a preferred option for the manager.

In what follows, we will study various situations of nuisance effects and damages caused by wild animals. The analysis is, however, restricted to situations where terrestrial animals cause direct damages, and the emphasis is all the time on large mammals. The models to be analysed are highly stylised and a traditional bioeconomic modelling approach is used. This means, among others, that a lumped parameter model, i.e., many parameters are collapsed into some few, gives the natural growth of the animals. Simple time invariant damage cost functions and cost functions for reducing the pest and nuisance are introduced as well. In some instances the nuisance species can also represent a value in the form of, say, meat or trophies. A simple benefit function, related to the harvesting, is then introduced in the same straightforward manner. The real world is clearly more complex; there are often more than one crop per year, there are lag effects between trapping effort and mortality, selective harvesting and trapping can take place, and so forth. All these simplifications are introduced to carry out a comprehensive and fairly general analysis where the basic questions are how to define a nature stock as an 'economic nuisance'; to what extent it is economic reasonable to harvest from a nuisance stock; when is it optimal to exterminate the nuisance; and under which circumstances make it most economic sense to live with the nuisance without any trapping.

As already indicated, we will basically think of wildlife causing damages on agricultural production. The following models have therefore a profit function related to crop production, which is reduced by the presence of wild animals. In section two we first analyse the pure nuisance case with no benefits related to the wild species. In a next step, in section three, an income stream of the wildlife when harvested or cropped, is introduced. This case is first analysed without harvesting costs while we next add costs. All the time we are thinking that the management is taking place at the farm level, or village level, with no non-consumptive value of the species included.

2. No value of the wild species, only nuisance

2.1 The model

As Zivin *et al.* (2000) we consider a landowner operating a piece of land with $A > 0$ as the crop profit, assumed to be fixed over time, in absence of damages. A population of wild animals X (measured in number of individuals, or biomass) at time t (the time notation is dropped) is eating up, or damaging the yield. The damage is given by $N = N(X)$, with $N(0) = 0$

and $\partial N/\partial X = N_X > 0$[2]. When normalising the damages to the crop profit (see, e.g., Carlson and Wetzstein 1993), the net agricultural profit reads

(1) $$U = A(1 - N(X)).$$

The costs of controlling the nuisance depend on the number of trapped animals, and the stock size. The cost function is formulated as

(2) $$C = c(X)h,$$

where h denotes the number of trapped animals. The cost is therefore assumed to be linear in the outtake, while the unit trapping cost $c(X) > 0$ is non-increasing in the stock abundance as trapping becomes progressively more difficult as the animal population becomes small, $c_X \leq 0$. In addition we have $c_{XX} \geq 0$.

The population growth is given as

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

where the stock grows according to the density dependent natural growth function $F(X)$. All the time we will think of 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 have no harvesting value, the management problem is to balance the crop benefit, decreasing in the size of the nuisance, with the control costs, increasing in the number of species removed, in an optimal way[3]. The optimisation problem is then to maximise the present-value net benefit

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[2] Zivin et al. use a linear damage function, $N = \alpha X$, $\alpha > 0$.

[3] In the present problem *A* is fixed and hence, there is no trade-off between effort use in crop production and trapping. A model studying this type of problem is found in Schulz and Skonhoft (1996).

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

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

We start by solving the model when assuming an interior solution. Extermination and living with nuisance in its starkest form, i.e., keeping the wildlife at its carrying capacity in the long term, is considered next.

2.2. Controlling the nuisance, but living with it

The current-value Hamiltonian of the above problem is $H = A(1- N(X))- c(X)h + \lambda(F(X) - h)$, where λ 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) $$-c(X) - \lambda = 0$$

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

Equation (5) is the maximum principle condition saying that harvesting should take place up to the point where the unit harvesting cost is equal to the shadow value of the animals, while equation (6) gives the portfolio balance equation. Equation (5) states clearly that, when only being a nuisance, the shadow price of the animals will be negative. Moreover, as the stock becomes smaller the shadow price should be even more negative due to increasing unit trapping costs.

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

(7) $$\delta = F_x\left(X^*\right) + \frac{\left[AN_x(X^*) + c_x\left(X^*\right)F\left(X^*\right)\right]}{c\left(X^*\right)}.$$

Hence, when having an internal solution, this equation alone determines the steady-state equilibrium stock X^*. In a next step, the number of animals trapped follows from equation (3) when $dX/dt = 0$, $h^* = F(X^*)$[4].

It is obvious that an optimal managed stock never will be larger if there is a nuisance effect linked to it than without the 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 $c_X F(X^*)$ and the marginal damage effect $AN_X(X^*)$. The cost effect depends on the marginal unit control term c_X and if its absolute value is large, it is optimal to have a small number of animals, $(d - F_X(X^*)) < 0$. This holds because the trapping costs are non-increasing in the stock size while the damage costs are increasing in the number of animals.

By introducing shift factors for the cost and damage functions and taking the total differential of equation (7), it can be confirmed that more nuisance means a smaller stock while higher harvesting costs mean more animals. These effects may seem to contrast the above condition for a small steady-state stock when the marginal control effect dominates the marginal nuisance effect, i.e., $(d - F_X(X^*)) < 0$. However, the marginal trapping cost can only be large for a small stock size. We also have that a more valuable crop means a smaller stock size, ¶X^*/¶$A < 0$. The effect of the rate of discount differs from what is found in the standard harvesting model (see, e.g., Clark 1990) as we obtain ¶X^*/¶$d > 0$. The reason is that there is no direct benefit from harvesting in the present model. Indeed, the situation is of the opposite, as effort must be used to keep the stock small, and the opportunity cost for this effort increases with a higher rate of discount.

The solution (7) can be illustrated by using the standard Gordon-Schäfer approach. The natural growth function is then $F(X) = rX(1 – X/K)$ where K, as already mentioned, is the carrying capacity while $r > 0$ is the maximum specific growth rate. In addition, we have the

[4] Thus, the 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 solution of the problem must obey a MRAP-strategy (Most Rapid Approach Path, see, e.g. Clark 1990) .

unit trapping cost function as *c(X) = a/X* with *a >0*. When assuming a linear damage function *N(X) =* aX with a *>0*, and the model has the same functional specifications as Zivin *et al*.(2000), the steady-state stock size yields[5] $X^* = \dfrac{d\,a}{a\,A - ra/K}$. Using these specific functional forms there must be restrictions on the damage cost coefficient a together with the value of the crop *A* to obtain an interior solution. The unit trapping cost *a* can neither be too small or too large; if it is large it is optimal too keep the species uncontrolled, if it is small it is optimal to exterminate the nuisance stock. In addition, it is seen that X^* approaches zero when the rate of discount approaches zero[6]. Extermination can therefore also be an option as well as keeping the nuisance at its carrying capacity. We now analyse these boundary solutions more closely.

2.3. Extermination of the nuisance or leaving it unexploited

Clark (1990, Ch. 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 first states that in the standard Gordon-Schaefer approach extinction is ruled out due to the infinite unit harvesting costs of extermination. However, as also Clark comments, this is unrealistic for many terrestrial species. This makes the pure Gordon-Schaefer approach unrealistic for studies where extermination is an economic option. Clark finds that extinction is optimal if the harvesting price is lower than the (constant) unit harvesting cost when the stock size is close to zero and if the rate of discount is substantial higher (two times) than that of the maximum specific growth rate of the species. His study concentrates on a nature asset stock – which will be left unexploited for a negative harvesting profit. Our case is opposite. We study a nuisance species, and the stock is a *liability* to the owner. The above analysis demonstrates, among others, that a valuable crop and large damages together with low trapping costs can make extinction an optimal policy. The same happens when there is no discounting and the damage function is linear.

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[5] Zivin et al. (2000) incorrectly states this condition as $X^* = da(aA-ra/K)$

[6] We obtain a slightly more general solution if the damage function is specified strictly convex, i.e., *N(X) =aX + (b/2)*X^2, with *b >0*. The steady-state stock size is then $X^* = \dfrac{(ra/K - a\,A) + \sqrt{(ra/K - a\,A)^2 + 4Aabd}}{2Ab}$.

The same type of restrictions to obtain an interior solution as in the linear damage case are present except that ***d*** *=0* not implies $X^* = 0$.

These results become apparent when studying the conditions for approaching $X^* = 0$ when initially assuming a positive stock at the steady-state. To find the more precise conditions for extinction being an optimal policy, however, the present-value of the various programs have to be compared. Hence, the possibility for extinction can be viewed from two different angles; the one of looking at the conditions for X^* approaching zero when initially having $0 < X^* < K$, and the one of comparing the present-value profit of driving the species to extinction with that of keeping a positive stock size. The last evaluation method dominates the first one. Accordingly, when equation (7) yields a positive stock, it is no guarantee that this represents the overall optimal solution.

The policy of not living with the nuisance at all and make the species extinct is optimal if the net discounted profit from doing so exceeds the net discounted profit from the internal optimal solution. When neglecting the extinction time and hence, assuming that extermination takes place immediately, the present-value profit of having no species left is $PV^{**} = \int_0^{\infty} [A(1 – N(0))]e^{-dt}dt – E(X^0) = A/d – E(X^0)$ where $E(X^0)$ denotes the extermination cost function, depending on the initial stock size X^0. On the other hand, when having an internal solution, the present-value profit reads $PV^* = \int_0^{\infty} [A(1 – N(X^*)) – c(X^*)F(X^*)]e^{-dt}dt – E(X^0,X^*) =(1/d)[A(1–N(X^*)) – c(X^*)F(X^*)] - E(X^0,X^*)$ when again adding the cost function of reaching the optimal stock size, depending on the location as the initial stock size as well as the steady-state. It is assumed that $X^* < X^0$, and again that the steady-state is approached immediately[7,8]. The difference reads $PV^{**} - PV^* = (1/d)[AN(X^*) + c(X^*)F(X^*)] + E(X^0,X^*) - E(X^0)$. When assuming that the steady-states are approached immediately, extermination is therefore *always* the optimal policy as long as the cost of reaching X^* is larger than the cost of extermination. However, even if $E(X^0)$ dominates $E(X^0,X^*)$ extermination is always optimal for finite extermination costs if the net discounted value of the costs of the nuisance stock $(1/d)[AN(X^*) + c(X^*)F(X^*)]$ is large. Hence, under these conditions, equation (7) with $X^* > 0$, does not represent the overall optimal solution. This is a far more general conclusion than Zivin *et al*.(2000).

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[7] The optimal dynamics of approaching the internal steady-state is, as mentioned, of the MRAP-type The present assumption implies therefore a zero MRAP-time.

When, like Zivin et al., we use the linear damage function together with the Gordon-Schäfer approach it is possible to draw a more definitive conclusion. In this case, as already seen, $X^* = \dfrac{d\,a}{a\,A - ra/K}$ represents the interior optimal solution. The accompanying present-value profit reads $PV^* = [(A-ra)/d - a] - E(X^0,X^*)$ after some small rearrangements. The difference between the programs of extinction and that of living with the nuisance is accordingly PV^{**}-$PV^*=(ra/d + a) + E(X^0,X^*) - E(X^0)$. Within this model specification, extinction is therefore always optimal when d is small and $E(X^0)$ is finite. Moreover, if $E(X^0)$ dominates $E(X^0,X^*)$, extinction is optimal for *all* values of d. This opposes the conclusion in Zivin *et al*.(2000) who infer that extermination is optimal only when d =0. If the extermination cost is approximated by $E(X^0) = c(X^0)(X^0 - \bar{X}) = (a/X^0)(X^0 - \bar{X}) = \; a - a\,\bar{X}/X^0$ where $\bar{X}$ is the critical value of extinction[9], the difference reads $PV^{**} - PV^* = ra/d + E(X^0, X^*) + a\,\bar{X}/X^0 > 0$. Hence, under the present approximation of the extermination cost together with a linear damage function within the Gordon-Schäfer approach, extermination is *always* the optimal strategy[10]. In a situation where it is possible to comb the area for the nuisance species, the extermination costs equal a, getting rid of the nuisance in one big action.

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 and compared with the internal solution. Starting from $X^0=K$, the present-value profit of keeping the stock uncontrolled is $PV^{***} = \int_0^{\infty} A(1-N(K))\, e^{-dt}dt = A(1-N(K))/d$. We therefore have PV^{***}- PV^*= $(1/d)[c(X^*)F(X^*) - A(N(K) - N(X^*))] + E(X^0,X^*)$. Hence, when having small nuisance costs, a low value of the crop together with high trapping costs, the optimal policy is not to trap at all.

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[8] The presence of $X^0 \leq X^*$ with $E(X^0,X^*) =0$ works in the direction of an interior solution being a more favourable solution (see the main text below). However, it seems unreasonable to assume an initial stock lower than that of the steady-state. If so, it has been trapped unprofitable for a period of time.

[9] If we are thinking of X in number of species, $\bar{X}$ must be at least two - and, when culling the last animal, the stock is still positive (and the unit culling costs finite) .

[10] Even if extermination takes place immediately, it can be argued that as the stock becomes smaller, the unit trapping cost may become larger. If so, the extermination cost function reads $E(X^0)$ $= \int_{\bar{X}}^{X^0} c(X)dX = \int_{\bar{X}}^{X^0} (a/X)dX = a\ln(X^0/\bar{X})$. In the same manner we have $E(X^0, E^*) = a\ln(X^0/X^*)$.

Hence, under these assumptions we obtain $PV^{**} - PV^* = a[r/d + 1 - \ln(X^*/\bar{X})]$ and there is generally no clear conclusion except when δ is small.

When again using the linear damage function together within the Gordon-Schäfer approach, this difference simplifies to $PV^{***} - PV^{*} = (ra - AaK)/d + a + E(X^0, X^*)$. When looking at the interior solution, the condition for keeping the species uncontrolled is $X^* = \frac{da}{aA - ra/K} > K$ which reduces to $(ra - AaK)/d + a > 0$. This is the same condition as above except that the cost function for reaching the optimal stock internal size $E(X^0, X^*)$ is not included. Hence, studying the present-value difference between the programs of not trapping at all and trapping represents a more relaxed condition for leaving the stock uncontrolled.

The general conclusion is that the standard Gordon-Schäfer specification with linear damage function makes internal solutions unrealistic, and the manager must decide either to exterminate the stock or to leave it unexploited. Moreover, for finite extermination costs, extermination will always be the best policy when the rate of discount is small. Hence, in this case the manager will be willing to incur large costs for animal removal in exchange for an infinite benefit stream from larger crop yields.

2.4. Other control measures

The pure nuisance model can 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, and natural growth of the wild animals (see, e.g., Levhari and Withagen 1992)[11]. 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

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

when we also have trapping. The Hamiltonian is now $H = A(1 - N(X)) - c(X)h - qV + l(F(X,V) - h)$. When it is profitability to trap, but not exterminate the species, and to use the new control measure as well, $V^* > 0$, the first order conditions for maximum are $-q + lF_V(X,V) = 0$ 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

[11] Influencing the natural growth function can also be interpreted as if selective trapping is talking place.

(9) $$d = F_x\left(X^*, V^*\right) + \frac{\left[AN_x\left(X^*\right) + c_x\left(X^*\right)F\left(X^*, V^*\right)\right]}{c\left(X^*\right)}$$

and

(10) $$-\frac{q}{F_v\left(X^*, V^*\right)} = c\left(X^*\right)$$

in addition to $h^* = F(X^*,V^*)$. Condition (10) simply states that the marginal cost of using the new control measure should be equal the marginal trapping cost[12].

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, however, not 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 $[c(X^*)F_{xv}(X^*,V^*) + c_x(X^*)F_v(X^*,V^*)] > 0$. Only when $F_{xv}(X^*,V^*) \geq$ the nuisance stock is therefore unambiguously smaller when having the additional control measure. The comparative statics in the extended model are just as in the basic model analysed above. In addition ¶X^*/¶$q > 0$ holds.

3. The nuisance is also representing a value

3.1 No harvesting costs

Above the wild animals represented only nuisance. However, in many instances the animals, when removed, also yield a value in the form of meat, or trophies. We then typically have a situation with large mammals with hunting as the control measure. Elephants and other wildlife in African countries clearly fit to this case (see, e.g., Bulte and van Kooten 1999), but large mammals in other localities also frequently represent both a nuisance and a harvesting value. Moose causing grazing damages on the one hand while representing a valuable hunting resource on the other hand is one example (see, e.g., Seather *et al.* 1992 for evidence from Scandinavia), and white-tailed deer in the United States is another example (Rondeau 2001). See also the feral pig example in Zivin *et al.* (2000).

[12] The dynamics of this control problem is also of the 'bang-bang' type for the variable *h*. The dynamic path of *V* adjusts accordingly through equation (10).

The management problem now is to balance the cropland benefit, decreasing in the size of the wild species, and the control benefit, increasing in the number of animals hunted, in an optimal way. Consequently, when hunting permits are sold at the price $p > 0$, assumed to be fixed and independent of the offtake and the size of the population, and the hunters bear the hunting costs and derive the utility from hunting, the problem is to maximise

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

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

The first order conditions are $p - l = 0$ and $dl/dt = ld + AN_X(X) - lF_X(X)$ when we have an interior solution. The shadow price is therefore now clearly positive and fixed, irrespective of the fact that the wild species also represents a nuisance[13]. The reduced form long-term equilibrium condition yields

$$(12) \qquad d = F_x\left(X^*\right) - \frac{AN_x\left(X^*\right)}{p}.$$

The location of X^* will now always be at a point characterised by $(d - F_X(X^*)) < 0$, determined by the size of the marginal nuisance *relative* to the harvesting price. The stock size will therefore also now be smaller compared to a situation without nuisance, i.e., when $N_X(X) = 0$. Thus, it is always optimal to remove animals and the stock will never be left unexploited. This result can also be confirmed by calculating the present-value profit. When also now ignoring the time of reaching the steady-state, we find $PV^* = (1/d)[A(1-N(X^*)) + pF(X^*)] + p(X^0 - X^*)$ where last term replaces the previous extermination cost function and represents the

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[13] Assuming the harvesting price to be unaffected by the number of animals harvested and 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 $p(1 + p_h h/p) = l$. Hence, the shadow price can, depending on the size of the demand elasticity, be negative. If so, the optimal nuisance can be at a point where $(d - F_X(X^*)) > 0$ holds (see the main text). This case is considered in Zivin *et al.*(2000). They also discuss a situation with both trapping and hunting as options at the same time, demonstrating that hunting is optimal even for a negative price as long as hunting is cheaper than the cost of trapping.

immediate harvesting value *gain* of reaching the steady-state when still assuming $(X^0 - X^*) > 0$. Consequently, we have $PV^{***} - PV^* = -(1/d)[A(N(K)–N(X^*)) + pF(X^*)] - p(X^0-X^*) < 0$. This result is quite obvious as harvesting now represents profit, and at the same time reduces the nuisance cost.

While the stock will never be left unexploited, it can, as in the pure nuisance model, be optimal to exterminate it. From condition (12) it is evident that a low harvesting price, a valuable crop together with high marginal damages work in the direction of X^* approaching zero. As in the pure nuisance model, however, extinction can represent the overall optimal policy even if X^* is positive. The present-value of extinction is now $PV^{**}=A/d + pX^0$, and hence, $PV^{**}- PV^*= (1/d)[AN(X^*) - pF(X^*)]+ pX^*$. Hence, extermination represents the overall optimal policy if the nuisance value dominates the harvesting value.

When again using the Gordon-Schäfer model together with the linear damage function, we now find $X^* = \frac{((r-d)p - aA)}{2rp/K}$. Substituting for X^*, $PV^{**}- PV^*= (X^*/2d)[Aa -(r - d)p]$ is the result after some small rearrangements. Under the present assumptions, the condition for extinction is therefore the same either by evaluating the present-value profits or by looking at the condition for X^* approaching zero.

3.2 Harvesting costs

The present case when wild animals have a value can be analysed somewhat more general when a harvesting cost also is included in the management problem. The net hunting benefit is then

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

with $b(X)$ as the unit profit, non-decreasing in the stock size, $b_X = -c_X \geq 0$. Contrary to the standard harvesting problem with no nuisance, $b(X)$ can be positive as well as negative. The two preceding models are therefore nested by this one with the pure nuisance case as $b(X) = -c(X) < 0$ and the value case as $b(X) = p > 0$. Observe that setting $b_X \geq 0$ also can be interpreted as the situation where increased stock makes the hunting permits more valuable for larger stocks (cf. footnote 12).

The present value benefit reads

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

with first order conditions for maximum as $b(X) - l = 0$ and $dl/dt = ld + AN_X(X) - b_X(X)h - lF_X(X)$ when assuming an interior solution. The shadow price can, depending on the stock size and hence, the unit harvesting cost, now therefore be positive or negative and hence, the wild animals can represent either a value or a nuisance.

The reduced form steady-state equilibrium follows as

(15) $$d = F_x\left(X^*\right) + \frac{\left[F(X^*)b_x\left(X^*\right) - AN_x\left(X^*\right)\right]}{b\left(X^*\right)}.$$

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, $(d - F_X(X^*)) >0$ holds when the cost term $F(X^*)b_X(X^*)$ 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 $(d - F_X(X^*)) <0$ 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.

By differentiating condition (15), we now 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^*. When the harvesting profit $b(X^*)$ is positive and the nuisance term dominates the cost term and hence, we have a small stock size, $(d - F_X(X^*)) <0$, the price effect is positive, ¶X^*/¶$p >0$. On the other hand, for a negative harvesting profit and a dominating nuisance term, $¶X^*/¶p < 0$ holds. Consequently, a higher price makes it less costly to deplete a non-valuable stock. When $b(X^*) <0$, we also obtain $¶X^*/¶d >0$, i.e., the same result as in the pure nuisance case. Again effort must be used to keep the stock small, and the opportunity cost of this effort increases with a higher rate of discount. When $b(X^*) >0$ holds, we therefore arrive at the standard result of $¶X^*/¶d <0$.

Also now it can add insight to illustrate the solution by using the Gordon-Schäfer approach together with the linear damage function $N(X) = aX$. The steady-state stock yields then $X^* = \frac{[ra/K - aA + (r-d)p] + \sqrt{[ra/K - aA + (r-d)p]^2 + 8rpad/K}}{4rp/K}$. 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 can neither be too small or 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, to find the more precise conditions whether extinction represents the optimal policy or keeping the species unexploited is the optimal policy, the present-value of the various programs have to be compared. Under the same assumptions as above, we now have $PV^* =(1/d)[A(1–N(X^*)) + b(X^*)F(X^*)] + p(X^0-X^*) - E(X^0,X^*)$ and $PV^{**} =A/d + pX^0 - E(X^0)$. Hence, the difference reads $PV^{**}- PV^* =(1/d)[AN(X^*)) - b(X^*)F(X^*)] + pX^* + E(X^0,X^*) - E(X^0)$. 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; that is, extermination is always optimal as long as the cost of reaching X^* is larger than the cost of extermination. Once again, extermination is therefore a relevant option to study.

4. Summary and concluding remarks

We have studied three different theoretical models of an ecological nuisance. The setting has been a large wild mammal species damaging the agricultural crop at the farm, or at the village level, and we are basically thinking about poor rural communities. Our analysis demonstrates that nuisance resources will be managed quite different from valuable resources. First, it is obvious that the manager will deplete the nuisance stock compared to a situation without any damaging effect. Second, the stock will only be left unexploited if the damage effect is small, and harvesting yields a negative profit. Third, at the farm or village level, it may very well make sense to eradicate the nuisance species. Two main problems have been highlighted: First, a nuisance species constitutes a nature liability, which makes it necessary to reconsider the effects of policy interventions. Second, a nuisance species should be eradicated due to its effect on agriculture, and we specify the decision criteria for this decision.

In *the pure nuisance case* the species stock is only nuisance and gives no benefit. We find that a valuable crop combined with large damages and a small trapping cost will motivate for keeping the nuisance small. On the contrary, a low value of the crop, small damages, difficulties in trapping the animals together with a high opportunity cost of alternative assets mean a low trapping intensity and a large stock. Such economic and ecological forces represent therefore the scenario of 'living with the nuisance'. It can also be optimal not to trap at all and keep the nuisance at its carrying capacity. The opposite management rule of eradication takes place when the crop is valuable, the damages are large or the rate of discount is small, suggested that the eradication cost is finite. In this case the manager will be willing to incur costs for total animal removal in exchange for an infinite benefit stream from larger crop yields.

The possibility of eradication as well as the option of not trapping at all, are studied both by looking at the conditions for an internal optimal solution approaches the boundaries, and by comparing the present-value profit of the various programs. As present-value maximisation is the management goal, the last evaluation method dominates the first one. Accordingly, when the internal optimal solution yields a positive stock, it is no guarantee that this represents the overall optimal management rule. This evaluation scheme is missing in the recent paper by Zivin *et al*. (2000), and hence, their analysis has serious shortcomings. For example, using a Gordon-Schäfer model together with a linear damage function, they infer that extinction is the optimal management rule *only* when there is no discounting. Contrary to this, when evaluating the present-value profits, we find that extinction, depending on the size of the eradication cost, can be the best option even for a high value of the rate of discount. The analysis supports that a nuisance stock without any harvesting value only will be safeguarded from extinction by its eventually large eradication costs.

In many instances animals, when removed, also yield a value in the form of meat or trophies, and this situation is also studied. We now find that the species never will be left unexploited, and the management plan includes always some trapping or hunting. The reason is that harvesting now represents profit while at the same time it reduces the nuisance cost. Just as in the pure nuisance model, however, the optimal management rule can be to eradicate the species. Again this happens if the crop is valuable and it is large crop damages. In addition, the harvesting value must be low. Moreover and contrary to the pure nuisance model, a high rate of discount works in the same direction.

Finally, we analyse the more general case of having a harvesting value together with costs of removing the species. The optimal management rule is then somewhat more complicated than the two other cases as the shadow price of the species now either is negative or positive. It is negative if the unit harvesting cost is above that of the harvesting price and hence, the species are harvested with negative profit. This model demonstrates how the management of a net liability differs from that of a net asset. When the harvesting yields negative profit, an increased rate of discount motivates for keeping a larger stock. Future costs of the nuisance are given less weight as a liability. On the other hand, an increased rate of discount yields the standard result of a smaller stock when having positive harvesting profit and the animals represent an asset. The effect of a higher harvesting price is also different whether the animal stock is a liability or a net asset, or more precisely whether the number of the species is small or not. If small, an increased harvesting value motivates for more animals, and vice versa.

The present management problem is analysed at the farm (or village) level, with no non-consumptive value of the species included. From a *social* point of view, however, values reflecting existence value, or biodiversity, should be included. Extinction, or small and threatened stock sizes, will then rarely represent an optimal social solution. It is therefore room for introducing policy measures to increase the wildlife stock due to its social value. The traditional way is to impose a ban on harvesting (see, e.g., Kiss 1990). Suggested that the ban is effective, this will obviously work in the right direction when the wildlife is only a nuisance and has no value at the farm level. However, if the species has a harvesting value, a ban on harvesting depressing the meat or trophy price, can work counterproductive and give fewer animals. This will always happen when it is no harvesting effort as the value of the species then reduces relatively to the crop damages. The same happens as well when a harvesting cost is included in the management problem and the stock is small, irrespective of positive or negative harvesting profit. Policy measures increasing the harvesting value, will therefore often work better in a conservation context. Moreover, to safeguard a small nuisance stock from extinction, one needs always to ensure that the wild animals have a net *value* at the farm or village level.

The value of crop production is also important for the management of the nuisance as 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. The reason is straightforward as the opportunity cost of keeping wildlife increases when the profitability in crop production increases. This supports the conclusions from Schulz and Skonhoft (1996) analysing the conflicting land-use between agricultural production and land made up for habitat.

References

Bulte, E.H. and G.C. van Kooten 1999: Economics of anti-poaching enforcement and the ivory trade ban. *American Journal of Agricultural Economics*, 81, 453-466.

Carlson, G.A. and M.E.Wetzstein 1993: Pesticides and Pest Management. In G. A. Carlson, D. Zilberman and J.A. Miranowski (eds.), *Agricultural and Environmental Economics*. Oxford UP, Oxford.

Clark, C.W. 1990: *Mathematical Bioeconomics: the Optimal Management of Renewable Resources (2th ed.)*. Wiley Interscience, New York.

Conway, G. 1981: Man versus pest. In R. May, *Theoretical Ecology*. Blackwell, Oxford.

Flaaten, O and K. Stollery 1996: The economic cost of biological predation. *Enviroment and Resource Economics*, 8, 75-95.

Hone, J. 1994: *An Analysis of Vertebrate Pest Control*. Cambridge University Press, Cambridge.

Kiss, A. (ed.) 1990: *Living with Wildlife*. The World Bank Environment Division, Washington DC.

Levhari, D. and C. Withagen 1992: Optimal management of the growth potential of renewable resources. *Journal of Economics*, 56, 297-309.

Rondeau, D. 2001: Along the way back from the brink. *Journal of Environment Economics and Management* 42, 156-182.

Saether, B. E., K. Solbraa, D. Soedal and O. Hjeljord 1992: Moose, forest and society. *Research Report* Norwegian Institute for Natural Research, Trondheim.

Schulz, C-E. and A. Skonhoft 1996: Wildlife Management, Land Use and Conflicts, *Environment and Development Economics*, 1, 265-280.

Skonhoft, A. and J.T. Solstad 1998: Investing in Wildlife: Can Wildlife Pay it's Way?, *Journal of African Economics*, 7, 237-262.

Swanson, T. 1994: *The International Regulation of Extinction*. Macmillan, London.

Swanson, T. and E. Barbier 1992: *Economics for the Wilds*. Island Press, Washington DC.

Tisdell, C. 1992: *Wild Pigs: Environmental Pest or Economic Resource*. Pergamon Press, Sidney.

Zivin, J., B.M. Hueth and D. Zilberman 2000: Managing a Multiple-Use Resource: The Case of Feral Pig Management in California Rangeland. *Journal of Environmental Economics and Management* 39, 189-204.

Wright, R. G. 1999: Wildlife management in the national parks: Questions in search of answers. *Eclogical Applications*, 9, 30-36.