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A Market-Based Approach to Manage Endangered Species Interactions

by

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Abstract

An economic activity interacts with an endangered species. The activity can be divided into mutually exclusive strata with different levels of interaction. Observing the activity in order to monitor interactions is costly. It may be desirable to manage the activity with a probability model which balances the benefit from the activity against the cost of the interaction with the endangered specie instead. The model gives rise to a permit scheme which fixates the risk of interaction over all strata and which uses the market mechanism to optimally allocate the activity between strata. The model can facilitate uncertainty in interaction rate estimates.

1 Introduction

Many economic activities interact with endangered species. In the U.S., endangered species interactions are treated under the Federal Endangered Species Act. Economists have criticized the Endangered Species Act for disregarding the incentives it creates, for its lack of scope for cost-benefit analysis (List et al. 2006), for its lack of attention to the distribution of costs, and how it 'places endangered species beyond the reach of economic tradeoffs, and [how] the economist is relegated to helping find the least cost solution to achieve a biological-based standard' (Brown and Shogren 1998, pp. 3, 10). The main focus of our analysis is exactly to find the least cost solution to achieve a standard through a market-based approach. (Whether the standard arises from a biological assessment only or a cost-benefit analysis is not of our primary interest here, although the latter clearly would be preferable.) More specifically, we suggest a tradable permit scheme which controls the risk of interactions between an economic activity and an endangered species across areas, periods, or technologies (across strata). The activity in the different strata is exposed to interactions at different levels. The market-based permit scheme leads interactions (that is, costs) to where the benefit of their cause (the economic activity; production) is maximized. Or rather, production is lead to its most efficient strata.

The basis for the permit scheme is a probability model of endangered species interactions. The model can be used to determine a level of activity which complies with a given level of interactions (a given standard). When interactions are spread over several strata with different interaction patterns or levels, the model can further determine how the activity can distribute across the strata in different ways, all complying with the given standard. A competitive market for activity permits will lead the distribution of activity to economic efficiency. (In theory, a fee or tax system would provide the same, efficient outcome under no uncertainty. Fees have primarily been used to improve environmental quality, however, while marketable permits primarily have been used to minimize costs (Hahn 1989, p. 108).)

The proposed permit scheme bear resemblance with cap-and-trade systems well-known from the pollution literature. Perhaps the most important difference is that while in a typical cap-and-trade system, a hard cap which cannot be exceeded is enforced, our permit scheme implies only a soft cap, which is not exceed with a chosen probability. A soft cap may be convenient with regard to endangered species, which, by their very nature, are rare, and monitoring costs may become prohibitive. A hard cap, on the contrary, requires close monitoring. Further, a realistic environmental quality constraint should be formulated in probabilistic terms given the stochastic nature of the externality (Beavis and Walker 1983, pp. 103, 105). The permit scheme also bears resemblance with water quality trading programs; see Shortle and Horan (2008) and references therein.

An example of hard caps on endangered species is the caps placed on leatherback and loggerhead turtles in the Hawaiian longline swordfish fishery. In order to enforce the hard caps, onboard biological observers are present on each fishing trip; 100% onboard observer coverage is required Gilman et al. (2007, p. 20). The fishery is closed for the remainder of the season once a cap is met.

Over 20 years ago, Hahn (1989, p. 112) reported that marketable pollution permits have a 'demonstrable effect in cost savings without sacrificing environmental quality' and predicted a more widespread use. While pollution and endangered species interactions are quite different issues, they do share structural properties like externality and incentive problems. Permits have not, however, become a regular instrument to help protect species: In 2002, only 3 % of incentive-based approaches to encourage species habitat conservation on private land in the U.S. involved market institutions, with permits representing only a share (Shogren 2005, p. 10). There is potential for a wider use of marketable permits when addressing endangered species conservation.

2 A Model of Endangered Species Interactions

The economic activity interacts with the endangered species in strata A and B. (The model extends to any number of strata.) The strata can represent a spatial, temporal, technological, or basically any dimension. Interactions are random processes (see for example, Segerson 2007) and follow distributions $p_A(a)$ and $p_B(b)$ in the two strata; a and b are vectors of distribution parameters. A given level y of interactions is found safe, and the goal is to find levels of activity in the strata such that the interaction level is at or below the safe level. Since interactions are random, the only way to guarantee that interactions stay below any level is to prohibit the activity in entirety. (In theory, a random interaction process can lead to any number of interactions on the first unit of activity. If the number of possible interactions per unit of the activity is limited, however, the level of allowable activity may be positive. In the following, we assume no such limitation.) If we allow the safe level to be kept only with a probability α, however, distributions p_A and p_B yields the levels X_A and X_B of allowable activity in each stratum given that no activity occurs in the other stratum. That is, the level X_A of activity in stratum A results in interactions in stratum A at or below the safe level with probability α ($\mathsf{Prob}(y_A \leq y) = \alpha$). Interactions are above the safe level with probability $1 - \alpha$. Presumable, the choice variable α would be set fairly close to one in many cases.

When the safe level holds only to a given probability, the environmental quality constraint is formulated in probabilistic terms; we call it a soft cap. Our formulation is essentially equivalent to the environmental quality standard suggested already by Beavis and Walker (1983, see equation (4), p. 105) Figure 1 illustrates the idea behind the soft cap. The area market as the 'Critical Area' must remain smaller than α.

The levels of activity, X_A and X_B, corresponding to the given safe level of interactions are corner solutions in the sense that all activity takes place in one stratum. (To be sure, X_A and X_B depend on the probability distributions and the probability level of success.) Typical efforts to protect endangered species involve corner solutions through protection (closing) of strata to activity. It may be desirable, however, to allow some activity in several strata, but still control the level of interactions to the probability α. Given that the total level of interaction y is the only level of interest, in other words, it is irrelevant in which strata an interaction takes place, an exchange rule of activity between strata can be set up. The rule is founded on probability distributions of interactions (p_A and p_B), the safe level of interactions (y), and the success probability level (α). The nature of the rule depend in particular on the probability distributions.

Before discussing the nature of the activity exchange rule, I want to motivate the need for exchange. Irrelevance of stratum of interaction is already

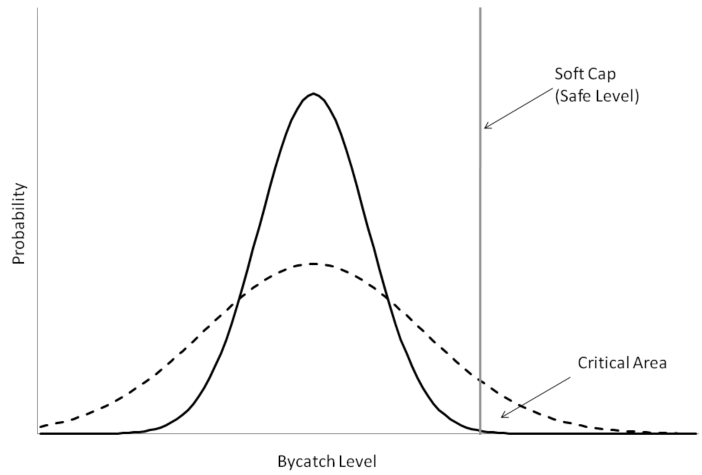

Figure 1: Illustration of the soft cap with two different probability distributions. The cap is reached when the 'Critical Area' is larger than α.

established. If also stratum of activity is irrelevant, activity should take place in the stratum with highest allowable level of activity; if $X_A > X_B$, activity should take place in stratum A. That is, activity should take place in the stratum with lowest probability of interaction. If the activity has different levels of profitability across strata, however, exchange may improve the total outcome. A market-based allocation of activity between strata, where activity levels are constrained to acceptable risk levels of endangered species interactions, is as least a good as any centrally planned allocation.

3 A Permit Exchange System

When a safe level of interactions (y), corner solutions (X_A, X_B), and an exchange rule of activity between strata have been established, an activity market can lead activity to the strata where it is most profitable. If the level of activity is controlled through permits, where permits can be exchanged between strata following the exchange rule of activity, a market for permits can be set up. Given a competitive market , the market value of a permit in a given stratum will be equal to the market value of an exchanged permit times the number of permits acquired from the exchange. An exchanged permit from stratum A results in, say, n permits in stratum B. Say further that the market value of a permit in stratum A is c_A, and c_B in stratum B. A competitive equilibrium leads to

$$c_A \cdot 1 = c_B \cdot n$$

A market will force all permits in a stratum to the same price; the price can however depend on a range of exogenous factors, like weather and the general price level. In the particular case where (i) the exchange rule is linear, that is, when permits are exchange at a fixed rate independent of the number of permits exchanged, and independent of the number of permits already issued for any strata, and (ii) the market value of a permit is independent on the number of permits in the different strata (the activity has constant returns to scale), all permits will flow to the strata with the highest market value of the corner solution. The market value of a corner solution is given by $c_i \cdot X_i$. For example, if $c_A \cdot X_A > c_B \cdot X_B$, all permits will flow to stratum A. Potentially more interesting situations occur if the exchange rule is nonlinear ((i) does not hold) or if the activity has increasing or decreasing returns to scale ((ii) does not hold).

The fundamental nature of the exchange rule is to maximize the number of permits in one stratum, given the number of permits in all other strata and the safe level of interactions. Generally, the exchange rule can depend on the distribution of permits; the exchange scheme between two strata can be concave, linear, or convex. The exchange rule depend on the joint probability distribution $D(y_A, y_B)$; y_A and y_B are interactions in the two strata. Formally, the joint probability distribution is defined as the joint, cumulative distribution of the two random processes y_A and y_B. Since stratum of interaction is irrelevant, the only condition on interactions is

$$y \geq y_A + y_B$$

where, again, y is the safe level of interactions. The condition securing the safe level of interactions with probability α is

$$D(y_A, y_B) \geq \alpha \tag{1}$$

Equation (1) is equivalent with $\mathsf{Prob}(y \geq y_A + y_B) \leq \alpha$. Since the distribution of interactions between strata is irrelevant, we may write $D(y)$ without ambiguity.

The exchange rule dictates the exchange rate of permits between strata from the following procedure. The number of permits in the two strata prior to the exchange are x_A and x_B. Exchanging one permit from stratum A to stratum B results in n stratum B permits such that both

$$D(y)[x_A - 1, x_B + n] \geq \alpha$$

and

$$D(y)[x_A - 1, x_B + n + 1] < \alpha$$

holds. That is, the safe level condition (1) holds for the new distribution of permits, $(x_A - 1, x_B + n)$, and the new number of permits is the maximum allowable such that (1) holds; increasing it with one violates the safe level condition. Thus, we can trace out the rule of exchange for permits between strata when $D(y)$ is known, or rather, when p_A and p_B are known.

The exchange rule has a simple, analytical representation when the probability distributions p_A and p_B are of specific types. Its numerical representation is at any rate fairly simple; the appendix explains a numerical scheme which provides the exchange rule for any $p_A(a)$ and $p_B(b)$. In the following, we discuss a few, common distributions and the exchange rule which arises in the different cases. We focus on distributions typically used to describe rare events, namely the Poisson and the Negative Binomial distributions, but we also describe the exchange rule from Normally distributed interactions. As it turns out, the key element is how the parameters a and b relates to the joint distribution $D(y)$; α only dictates the level of the relation.

3.1 Poisson Distributed Interactions

When the probability distributions of interactions, $p_A(a)$ and $p_B(b)$, are Poisson distributions, the parameter vectors a and b have only one element.

$$p_A(a) = \text{Pois}(a) = \frac{a^{y_A} \mathrm{e}^{-a}}{y_A!}$$

$$p_B(b) = \text{Pois}(b) = \frac{b^{y_B} \mathrm{e}^{-b}}{y_B!}$$

y_A and y_B are the number of interactions in the strata. The parameter element must incorporate both the rate of interaction and the level of activity; let r_i denote the interaction rate per unit activity and x_i the activity level in stratum i. Then, $a = r_A \cdot x_A$, and similarly $b = r_B \cdot x_B$; the distribution parameter is the expected number of interactions, $\mathrm{E}[p_A(a)] = a$. Let $\Sigma y = y_A + y_B$; the total number of interactions is the sum of interactions in the different strata, where both y_A and y_B are Poisson distributed random variables with parameters a and b. Σy is then a Poisson distributed random variable with distribution parameter $\mu = a + b$ (see Ross 1985, p. 65, or Cameron and Trivedi 1998, p. 4). That is, the joint probability distribution for y_A and y_B is a cummulative Poisson distribution with parameter $\mu = a + b$;

$$D(y_A, y_B) = \text{Pois}_{\text{CDF}}(a + b)$$

To secure the safe level y with probability α, that is, condition (1), one is required to find μ^* such that

$$\text{Pois}_{\text{CDF}}(\mu^*) \geq \alpha$$

μ^* is an implicit function of α. With μ^* given, the exchange rule of activity is then defined by

$$\mu^* = r_A \cdot x_A + r_B \cdot x_B \tag{2}$$

which is linear in the activity levels x_A and x_B. Let $r_A > r_B$. The exchange rule is thus only an implicit function of α. From (2), we get

$$\begin{aligned}\mu^* &= r_A x_A + r_B x_B \\ &= r_A(x_A - 1) + r_A + r_B x_B \\ &= r_A(x_A - 1) + r_B(x_B + \frac{r_A}{r_B})\end{aligned}$$

That is, exchanging one unit of activity from stratum A to stratum B yields $\frac{r_A}{r_B}$ units of activity in stratum B (rounded down to closest unit if necessary).

According to Greene (2003), the property that 'sums of random variables with a given distribution have that same distribution' is called the contagion property (p. 859). For the exchange rule to be linear in the activity levels, the parameters of the sum distribution must also be the sum of the parameters of the original distributions, a condition which does not hold for the binomial distribution, for example (see Ross 1985, p. 64).

The exchange rule is linear when interactions are Poisson distributed random variables (condition (i) above holds). The exchange rate of activity between strata is the ratio of interaction rates and is independent of activity levels x_i. The corner solution in stratum i is given by $X_i = \frac{\mu^*}{r_i} = \frac{r_j X_j}{r_i}$; see (2) with $x_{j \neq i} = 0$. If the market value of activity (c_i) is independent of the level of activity (see condition (ii) above), all activity flow to stratum i if and only if

$$\frac{c_i}{c_j} > \frac{r_i}{r_j} \tag{3}$$

since

$$c_i X_i > c_j X_j \quad = \quad c_j \frac{r_i}{r_j} X_i \quad \Leftrightarrow \qquad \frac{c_i}{c_j} > \frac{r_i}{r_j}$$

which uses the equalities

$$r_i X_i = \mu^* = r_j X_j$$

3.2 Negative Binomially Distributed Interactions

When the probability distributions of interactions, $p_A(a)$ and $p_B(b)$, are Negative Binomial distributions, the parameter vectors a and b have two elements.

The first element is the level of activity without interaction, n, the second is the probability of no interaction per unit of activity, $1 - r$.

$$\begin{aligned}
p_A(a) = \text{NegBin}(n_A, 1 - r_A) &= \binom{y_A + n_A - 1}{n_A - 1}(1 - r_A)^{n_A}\left(1 - (1 - r_A)\right)^{y_A} \\
&= \binom{y_A + n_A - 1}{n_A - 1}(1 - r_A)^{n_A} r_A^{y_A} \\
p_B(b) = \text{NegBin}(n_B, 1 - r_B) &= \binom{y_B + n_B - 1}{n_B - 1}(1 - r_B)^{n_B}\left(1 - (1 - r_B)\right)^{y_B} \\
&= \binom{y_B + n_B - 1}{n_B - 1}(1 - r_B)^{n_B} r_B^{y_B}
\end{aligned}$$

y_i is, as before, the number of interactions in stratum i. In this setup, only one interaction is possible per unit of activity and one can thus say that a unit of activity is either a success or a failure, depending on whether an interaction occurred (failure) or not (success). The setup may be cumbersome; notwithstanding, it is analogous to the standard interpretation of the negative binomial distribution.

To illustrate, the distribution $\text{NegBin}(n, 1 - r)$ with $n = 50$ and $r = 0.1$ is shown in Figure 2. At $y = 5$ it has $\text{NegBin}(n, 1 - r)_{y=5} = 0.163$, which means that there is a 16.3% probability of 5 failures (interactions) before 50 successes (no interactions) has occurred.

An analytical treatment of the exchange rule under negative binomially distributed interactions is, as far as we know, beyond reach. Numerical experimentation, however, suggest that the exchange rule is linear as in the Poisson distribution case (for the numerical scheme, see the appendix). The rule can thus be represented similarly as the Poisson exchange rule (2):

$$\phi^* = s_A x_A + s_B x_B$$

ϕ^*, s_A, and s_B are all constants, but has a less immediate interpretation than the constants in (2). The same development as earlier applies, however. Thus, if $s_i > s_j$, exchanging a permit from stratum i results in $\frac{s_i}{s_j}$ stratum j permits. Corner solutions follow from $\phi^* = s_i X_i$. Finally, if condition (ii) holds, all activity flow to stratum i if and only if $\frac{c_i}{c_j} > \frac{s_i}{s_j}$.

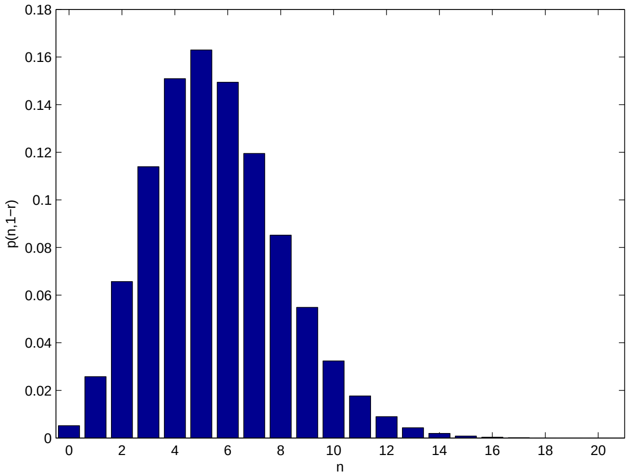

Figure 2: The Negative Binomial distribution, $\text{NegBin}(n, 1 - r)$ with $n = 50$ and $r = 0.1$.

3.3 Normally Distributed Interactions

Finally, we look at interactions which are normally distributed. The normal distribution may not be the most ideal to model presumably rare events such as endangered species interactions. For the sake of argument, however, let the interactions follow normal distributions $p_A(a) = N(\mu_A, \sigma_A^2)$ and $p_B(b) = N(\mu_B, \sigma_B^2)$. The joint distribution is then also normal with parameters $x_A\mu_A + x_B\mu_B$ and $x_A\sigma_A^2 + x_B\sigma_B^2$ (Ross 1985, p. 65). As before, x_A and x_B are the activity levels in the two strata. We have

$$D(y_A, y_B) = \int_{-\infty}^{y} \mathrm{N}(x_A\mu_A + x_B\mu_B, x_A\sigma_A^2 + x_B\sigma_B^2)\mathrm{d}\tilde{y}$$

where $\tilde{y} = y_A + y_B$. Let the number of interactions stay below the safe level y with probability α for parameters (μ^*, σ^{2}). We have

$$\begin{aligned} \mu^* &= x_A\mu_A + x_B\mu_B \\ \sigma^{*2} &= x_A\sigma_A^2 + x_B\sigma_B^2 \end{aligned}$$

The system is linear in the activity levels x_A and x_B as under Poisson distributed interactions. The system is overdetermined, however. The first equation dictates that (assuming $\mu_A > \mu_B$) exchanging one unit of activity from stratum A to stratum B yields $\frac{\mu_A}{\mu_B}$ units of activity in stratum B (the development follows that following equation (2)). Similarly, from the second equation, the exchange should yield $\frac{\sigma_A^2}{\sigma_B^2}$ units of activity in stratum B. The thightest constraint binds, such that if $\frac{\mu_A}{\mu_B} < \frac{\sigma_A^2}{\sigma_B^2}$, the first equation dictates the exchange rule, and vice versa.

Let $\frac{\mu_A}{\mu_B} < \frac{\sigma_A^2}{\sigma_B^2}$. As with the Poisson distributed interactions, all activity flow to stratum i if an only if

$$\frac{c_i}{c_j} > \frac{\mu_i}{\mu_j}$$

which corresponds to (3).

4 Example: Poisson Distributed Turtle Interactions

The drift gillnet fishery for shark and swordfish along the U.S. western coast interacts with the endangered Pacific leatherback turtle (Carretta et al. 2004, see Spotila et al. 2000 for more on the endangered leatherback turtle).[1] The interaction pattern can be modeled as a Poisson distributed random process (Kvamsdal and Stohs 2009, pp. 102-103) and the fishery can be divided into two mutually exclusive strata. The rate of interaction in the two strata are approximately $r_A = 10$ and $r_B = 1$ per thousand units of fishing activity in the two strata (Kvamsdal and Stohs 2009, p. 118; as the example is only meant to illustrate the workings of a permit scheme across strata, the rates are, in order to keep things simple, rounded to the nearest integer). The safe level of interactions is, say, $y = 5$, and the safe level is required to be met with probability $\alpha = 95\%$. Corner solutions, the maximum allowable level of fishing activity in each stratum given no activity in the other stratum, are then $X_A = 261$ and $X_B = 2613$ units of fishing activity. The exchange rule is linear (condition (i) above holds) and follows (2); a stratum A permit can be exchanged for $\frac{r_A}{r_B} = 10$ stratum B permits.

[1] The example in this section is similar to the example in Kvamsdal and Stohs (2009, pp. 118–119).

In a competitive market for permits, the expected value of a permit equals its market value (c_i). If condition (ii) holds, that the market value is independent of the number of permits in the two strata, all permits will be used in stratum A if and only if

$$\frac{c_A}{c_B} > \frac{r_A}{r_B} = 10$$

See (3). Kvamsdal and Stohs (2009) discuss the example further and demonstrate how the permit scheme may improve, under certain conditions, the total outcome in the fishery when compared to the current seasonal turtle conservation closure.

It may well be that condition (ii) holds for the swordfish fishery as the fishery represents only a small share of the global swordfish catch. If condition (ii) does not hold, however, permits may be active in both strata. To illustrate, let the market value of stratum A permits decline in x_A (the number of permits in stratum A), $c_A = c_0 - x_A$, while $c_B = 1$. The exchange rule gives $x_A = \frac{r_A}{r_B} x_B$. In a competitive equilibrium, the market value of a permit times the inverse exchange rate must equal the market value of the exchanged permit (alternatively, the market value of a permit must equal the market value of a permit in the other strata times the exchange rate);

$$\begin{aligned} c_A \cdot \frac{r_B}{r_A} &= c_B \\ c_0 - x_A &= c_B \cdot \frac{r_A}{r_B} \\ x_A &= c_0 - c_B \cdot \frac{r_A}{r_B} \end{aligned}$$

If $c_0 = 100$, $x_A = 100 - 1 \cdot \frac{10}{1} = 90$ permits will be used in stratum A, and $x_B = X_B - x_A \cdot \frac{r_A}{r_B} = 2613 - 90 \cdot 10 = 1713$ permits will be used in stratum B. Market values of permits are $c_A = c_0 - x_A = 10$ and $c_B = 1$.

5 Final Remarks

The main idea behind our paper is that if interaction rates between an economic activity and an endangered species differ across strata, it is possible to construct a marketable permit scheme which lets authorities determine and enforce (to a given probability) the overall level of interactions while a market mechanism leads the distribution of activity towards the most efficient distribution.

We have formulated a requirement on the joint probability distribution (1) which can be interpreted as a soft cap on interactions; the interaction level may exceed the cap, but only with a small probability. We have also laid out a simple algorithm which traces out an exchange rule of permits between strata. The exchange rule keeps the interaction risk fixed. If interactions are described through either Poisson or Normal distributions, however, the exchange rule is linear. Numerical experimentation suggest that the exchange rule is also linear with Negative Binomially distributed interactions. A linear exchange rule may be valuable as it reduces the potential complexity of the permit scheme with a non-linear exchange rule. While not completely comparable, our exchange rules has a strikingly similarity to the 'trade ratios' Shortle and Horan (2008) develop for water quality trading; see for example equation (4), p. 117, and the surrounding discussion.

Perhaps the most critical assumption in our analysis is the requirement on reliable interaction rate estimates. Uncertainty in interaction rate estimates may be incorporated, however, by letting the probability distributions p_i represent the joint probability distribution of parameter estimates and the estimated distribution.

"[A] regulatory agency has three integrated tasks to develop a market for [externality] trading that is consistent with the achievement of an environmental goal" (Shortle and Horan 2008, p. 109). Restating the tasks for an interaction permit market, the tasks are (a): Define the tradable commodities in the market, (b): Define exchange rules between strata, (c): Limit the aggregate supply of the commodities such that the the environmental goal is not violated (Shortle and Horan 2008, pp. 109-110). Issuing activity permits and allowing exchange according to the rules we have established would ensure the environmental goal is met and completes the tasks outlined by Shortle and Horan (2008).

Boyd et al. (2000) has suggested so-called trading differentials in tradable development rights schemes (see Parkhurst and Shogren 2005, p. 94 for a discussion). The aim of tradable development rights schemes is to help conserve habitat for threatened species. The idea behind trading differentials is that areas which are more valuable as habitat trades for more in the market for development rights than less valuable areas. The idea is similar to the permit scheme suggested in this paper. The focus of our scheme is, however, interactions with endangered species and not conservation of habitat. (To be sure, 'interactions' can be defined broadly enough to include degradation of habitat.) One may, however, think of economic activities, such as fishing, which can take place in the habitat of a species without necessarily degrading or destroying it.

An important issue we have not touched upon in our analysis is how the safe level of interactions is determined. While it is beyond our scope to discuss it at great length, we do agree with Shogren et al. (1999, p. 1258) in that 'What is the desired level of species protection?' is an economic question; the safe level of interactions should be subject to economic trade-offs. The assertion resonates with the discussion in Beavis and Walker (1983, pp. 109-110)

Appendix

The numerical procedure is by no means 'optimized' with respect to computation time or elegance, but it is fairly simple to understand and implement. It does not depend on type of distributions nor that distributions are of the same kind.

To calculate the exchange rule for given distributions $p_A(a)$ and $p_B(b)$, the first step is to find the corner solutions X_A and X_B. Let $x_A = 1$ and $x_B = 0$ and calculate the cumulative probability at $y_A = y$ (the safe level of interactions). If the probability exceeds the probability limit α, increase activity level x_A with one unit and repeat. The probability limit will be not be exceeded for the first time at $X_A + 1$. Reverse A and B to find X_B. (If the exchange rule is known to be linear, no more calculations are necessary, the linearity can alternatively be controlled at some interior point.)

The exchange rule can now be traced out for all $x_i \in [0, X_i]$ with essentially the same procedure: Initially, let $x_B = 1$ and seek through x_A as before. The procedure produces, say, the activity level $\tilde{x}_A$, and the exchange rule is represented by the pairs $[\tilde{x}_A, \tilde{x}_B]$. (It is not necessary to compute both $\tilde{x}_A$ and $\tilde{x}_B$ as the procedure is symmetric.) Notably, it is now necessary to calculate the joint probabilities $D(y)[x_A, x_B = 1]$. One way to calculate this is to compute

$$p_A(a)[x_A]' p_B(b)[x_B = 1]$$

where the first factor is a column vector, the second a row vector, and compute the sum of skew diagonal ('northeast' direction) number y of the resulting matrix.

The whole procedure can be tedious and slow, and often it can be enough to compute the exchange rule at only a few interior points away from the corner solutions. A Matlab-script which computes the exchange rule for the negative binomial distribution case is available from the authors upon request.

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