Objectives for Multiple-Species Conservation Planning

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Abstract: *The first step in conservation planning is to identify objectives. Most stated objectives for conservation, such as to maximize biodiversity outcomes, are too vague to be useful within a decision-making framework. One way to clarify the issue is to define objectives in terms of the risk of extinction for multiple species. Although the assessment of extinction risk for single species is common, few researchers have formulated an objective function that combines the extinction risks of multiple species. We sought to translate the broad goal of maximizing the viability of species into explicit objectives for use in a decision-theoretic approach to conservation planning. We formulated several objective functions based on extinction risk across many species and illustrated the differences between these objectives with simple examples. Each objective function was the mathematical representation of an approach to conservation and emphasized different levels of threat. Our objectives included minimizing the joint probability of one or more extinctions, minimizing the expected number of extinctions, and minimizing the increase in risk of extinction from the best-case scenario. With objective functions based on joint probabilities of extinction across species, any correlations in extinction probabilities had to be known or the resultant decisions were potentially misleading. Additive objectives, such as the expected number of extinctions, did not produce the same anomalies. We demonstrated that the choice of objective function is central to the decision-making process because alternative objective functions can lead to a different ranking of management options. Therefore, decision makers need to think carefully in selecting and defining their conservation goals.*

Keywords: extinction risk, objective function, optimization, population viability analysis, reserve design

Objetivos para la Planificación de la Conservación de Múltiples Especies

Resumen: *La identificación de objetivos es el primer paso en la planificación de conservación. La mayoría de los objetivos de conservación, tal como maximizar la biodiversidad, son muy vagos para ser útiles en un marco de toma de decisiones. Una manera de clarificar el tema es la definición de objetivos en términos del riesgo de extinción de múltiples especies. Aunque la evaluación del riesgo de extinción de una especie individual es común, pocos investigadores han formulado una función de objetivos que combina los riesgos de extinción de múltiples especies. Tratamos de traducir el objetivo general de maximizar la viabilidad de especies en objetivos explícitos para ser usados en un método de decisión teórica de planificación de conservación. Formulamos diversas funciones de objetivos basados en el riesgo de extinción de muchas especies, e ilustramos las diferencias entre esos objetivos con ejemplos simples. Cada función de objetivo fue la representación matemática de un método de conservación y enfatizaba diferentes niveles de amenaza. Nuestros objetivos incluyeron la minimización de la probabilidad conjunta de una o más extinciones, la minimización del número esperado de extinciones y la minimización del incremento en el riesgo de extinción en el mejor escenario. Con las funciones de objetivos basadas en probabilidades conjuntas de extinción de las especies, cualquier correlación en las probabilidades de extinción debería ser conocida o las decisiones resultantes eran potencialmente erróneas. Objetivos aditivos, tal como el número esperado de extinciones, no produjeron las mismas anomalías. Demostramos que la elección de la función de objetivo es central en el proceso de toma*

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de decisiones porque las funciones de objetivos alternativas pueden llevar a una diferente clasificación de las opciones de manejo. Por lo tanto, los tomadores de decisiones deben pensar la selección y definición de sus metas de conservación cuidadosamente.

Palabras Clave: análisis de viabilidad poblacional, diseño de reservas, función de objetivos, optimización, riesgo de extinción

Introduction

The first task of conservation planning is to identify the overarching goal (Margules & Pressey 2000; Opdam et al. 2001). Government guidelines and legislation typically consist of vague goals and undefined terms, such as to "maximize species' viability" and "maintain viable populations" while "minimizing adverse impacts" (UNEP 1992; Commonwealth of Australia 1997). To be useable in decision making, broad goals need to be translated into definable and measurable objectives, the essential first step of a decision-theoretic approach (Metrick & Weitzman 1998; Westphal & Possingham 2003). Indeed, the inability to define explicit objectives has been identified as a significant problem in environmental management in marine and terrestrial systems (Sainsbury et al. 2000; Failing & Gregory 2003).

The persistence of biodiversity is the primary goal of systematic conservation planning (Williams 1998; Margules & Pressey 2000). However, our ability to incorporate biodiversity persistence directly is constrained by the difficulty in estimating it. Reserve-design methods aim to represent multiple species and ecosystems in a system of conservation areas. Additional goals can be set to address viability issues (for comprehensive reviews, see Cabeza & Moilanen 2001; Cabeza et al. 2004) but tend not to include an explicit measure of species' persistence (Witting & Loeschcke 1993). Examples of such goals include targets for population sizes or area of habitat (Cowling et al. 1999; Burgman et al. 2001), design criteria, such as minimizing fragmentation (Cowling et al. 1999; Possingham et al. 2000; Cabeza & Moilanen 2003), using information from population models (Carroll et al. 2003), and analyzing the vulnerability of a site to threatening processes (Cowling et al. 1999; Wilson et al. 2005*a*).

An alternative approach to including persistence is to formulate conservation objectives that directly incorporate the probability of persistence or extinction of multiple species (Hof & Raphael 1993; Bevers et al. 1995; Williams & Araújo 2000). The extinction risk (the probability of extinction over a finite time frame) of a species or a suite of species is one way to measure biodiversity persistence. Extinction risk provides us with a common currency across species to compare management decisions (Witting & Loeschcke 1993; Williams & Araújo 2002; Drechsler et al. 2003).

Some methods for estimating species' extinction risk can directly incorporate process into the estimate of extinction risk, such as stochasticity, the dynamics between the amount and configuration of habitat, and vulnerability to threatening processes (e.g., Possingham et al. 1994; Root et al. 2003; Frank 2005). Many approaches have been used to estimate species' extinction risk (Akçakaya & Sjögren-Gulve 2000), including expert opinion (Weitzman 1993; McCarthy et al. 2004), transformations of probabilities of occurrence (Araújo & Williams 2000; Williams & Araújo 2000), deterministic models (Hof & Raphael 1993; Bevers et al. 1995), stochastic approximation models (Nicholls et al. 1996; Frank 2005; McCarthy et al. 2005), and simulation models of population dynamics (Possingham et al. 1994; Akçakaya & Sjögren-Gulve 2000; Drechsler et al. 2003). Most applications of extinction risk consider only one species (e.g., Possingham et al. 1994; Hof & Raphael 1997; Calkin et al. 2002), an approach criticized for being inefficient and inadequate for the protection of nontarget species (Simberloff 1998; Andelman & Fagan 2000), leading to a call for conservation planning based on the persistence of multiple species (Akçakaya & Sjögren-Gulve 2000).

The extinction risk of more than one species may be used in many ways in conservation decision making. The simplest approach is to consider each species separately, without setting multiple-species objectives (Nicholls et al. 1996; Cabeza & Moilanen 2003; Carroll et al. 2003). Extinction risk can be combined with habitat suitability to give an index of conservation value of parcels of land (Akçakaya 2000; Root et al. 2003). Such an index can identify areas that are important for the persistence of the most species; however, the goals and constraints of the reserve system are not made explicit.

The extinction risk of more than one species can be combined directly to form a conservation objective (Hof & Raphael 1993; Weitzman 1993; Williams & Araújo 2000). The most commonly used forms of such objective functions, which we discuss further below, maximize the expected number of extant species (Hof & Raphael 1993; Williams & Araújo 2000; Camm et al. 2002), the probability of persistence of the species with the highest extinction risk (Hof & Raphael 1993; Bevers et al. 1995; Akçakaya 2000), and the probability that all species persist (Hof & Raphael 1993; Weitzman 1993; Bevers et al. 1995).

Here, we asked how the broad goal of maximizing the viability of species can be translated into specific conservation objectives for use in a decision-theoretic approach to conservation planning. We formulated objective functions based on extinction risk across many species and added new functions to previously published objectives. As in Williams and Araújo (2000), our purpose was to consider ways in which the information on the extinction risks of multiple species is used, rather than to review and critique the way in which the suite of species is selected (e.g., Lambeck 1997; Fleishman et al. 2000; Andelman et al. 2004) and their extinction risks estimated.

We extended the work of Hof and Raphael (1993), Bevers et al. (1995), and Williams and Araújo (2000) by questioning the underlying biases of alternative objective functions and investigating their impacts on conservation decisions. Because each objective function was the mathematical representation of a conservation goal and approach to conservation, we needed to consider a variety of conservation questions. Is the goal of conservation to minimize the chance of any extinctions occurring or to minimize the expected number of extinctions? Should the priority be highly threatened species or species whose extinction risks are most improved by conservation action? How do assumptions about correlations in extinction risks between species affect decisions? We illustrate the alternative objectives through a hypothetical example and demonstrate how the choice of goal affects the ranking of different conservation plans.

Problem Formulation and Notation

We addressed a typical conservation planning problem: deciding which areas to protect within a region. The same principles apply to making decisions for other conservation actions, such as habitat rehabilitation or revegetation (Opdam et al. 2001; Westphal & Possingham 2003). The selected areas, referred to as reserves, may be allocated a variety of protection measures, from national parks to off-reserve management (Margules & Pressey 2000). For the sake of simplicity, we described a binary system, where a site was either reserved or not reserved. This problem could be extended to allocate different management strategies to every site, for example, allocating varying intensities of extraction to different sites in forestry (Calkin et al. 2002).

We assumed that estimates of extinction risk over some time frame were available for a suite of species. We formulated objectives to use this information for decision making. Extinction risk may be absolute extinction or a quasi-extinction risk, the risk of a population decline (Burgman & Possingham 2000). Our objectives were in terms of extinction risk, and we did not account for the population size or trajectory that a species may have if it is not extinct.

The objective functions we describe could be used in either a post hoc assessment to rank alternative conservation plans, as in the example we present below, or an optimization problem. In an optimization framework, the maximal coverage approach is used, where the best conservation outcome is sought within a given budget (Williams & Araújo 2000; Camm et al. 2002; Westphal & Possingham 2003). We preferred this framework to the minimum set approach, where the cost of the reserve system is minimized subject to all species meeting an extinction probability threshold (e.g., Williams & Araújo 2000; Calkin et al. 2002; Williams & Araújo 2002). The use of thresholds of extinction risk runs counter to the literature on population viability analysis, which recommends the use of risks to compare options, rather than to meet a target with an uncertain estimate of extinction risk (Burgman & Possingham 2000; Drechsler et al. 2003; McCarthy et al. 2003). The maximal coverage approach also allows the trade-offs to be examined between different species and between conservation and socioeconomic benefits (Simberloff 1998; Williams 1998; Failing & Gregory 2003). Each of the objective functions was therefore minimized subject to a budget B, for example, funds allocated to land acquisition, revegetation, or forgone timber profits in a forestry region.

When considering a finite set of areas that may potentially be included in a system of protected areas, each area may be in or out of the system, and the state of the system can be described as a vector, $\boldsymbol{x}$, of 1s and 0s, where

$$x_j = \begin{cases} 1 & \text{if area } j \text{ is reserved} \\ 0 & \text{otherwise} \end{cases}.$$

For each potential conservation scenario, every species has a probability of extinction over a given time frame. Let the risk of extinction of species i, given reserve system x, be $p_i(x)$. For a given budget there may be many alternative conservation scenarios, some better and some worse for each species. The best scenario for species i, given the budgetary constraints, is given by $p_i(1)$, and by definition $p_i(x) \geq p_i(1)$. The best-case scenario may be the optimal solution per species, or it may be the best alternative available in a post hoc ranking problem, such as the example we present below.

Multiple-Species Objective Functions

We formulated seven objective functions, some of which have appeared in the literature and others that were new. Their merits and shortcomings for conservation planning are discussed in the following section and summarized in Table 1.

Table 1. Summary of objective functions used in a decision-theoretic approach to conservation planning.

Objective function	*Interpretation*	*Risk levels emphasized*	*Functional type*
1. Umbrella species: minimize $p_{\max}(x)$	threshold: minimizes the highest extinction risk	highest risk species	threshold
2. Joint probability of one or more extinctions: minimize $\left(1-\prod_{i=1}^{n}\left[1-p_i(x)\right]\right)$	state: minimizes the probability of being in the state of one or more species becoming extinct	tendency to moderate but equitable extinction risks	multiplicative
3. Joint probability of all extinct: minimize $\prod_{i=1}^{n} p_i(x)$	state: minimizes the probability of being in the state of all species being extinct	lowest risk species emphasized, with several extinctions allowed	multiplicative
4. Expected number of extinctions: minimize $\sum_{i=1}^{n} p_i(x)$	expectation: minimizes the expected number of extinctions	greedy: all increments equal; allows some high risks if balanced with low risks	additive
5. Increase in the expected extinctions: minimize $\sum_{i=1}^{n}\left[p_i(x)-p_i(1)\right]$	expectation: minimizes the increase in the expected number of extinctions from the best-case scenario	greedy: all increments equal; same as expected number of extinctions	additive
6. Proportional increase in extinction risk: minimize $\sum_{i=1}^{n}\frac{p_i(x)}{p_i(1)}$	metric: per species value is the proportional increase in extinction risk	species that benefit most from conservation action and at low risk under the best-case scenario	additive
7. Relative losses: high persistence and high risk: $\sum_{i=1}^{n}\left[\left(p_i(x)-\frac{4p_i(x)^2}{2}+\frac{4p_i(x)^3}{3}\right)-\left(p_i(1)-\frac{4p_i(1)^2}{2}+\frac{4p_i(1)^3}{3}\right)\right]$	metric: derived from a weighted version of the increase in the expected number of extinctions	high risk, lower risk; species that benefit from conservation action	additive

Umbrella Species

The umbrella species approach uses the species most at risk to make conservation decisions, based on the assumption that improving the lot of the umbrella species will allow other similar or co-occurring species to persist as well (Andelman & Fagan 2000; Fleishman et al. 2000; Roberge & Angelstam 2004). Generally, the species thought to be the most threatened is selected a priori as the umbrella species (e.g., Hof & Raphael 1997). Instead, we minimized the highest extinction risk among a suite of species, rather than the risk of the most threatened species. This approach has been used as an objective function (Hof & Raphael 1993; Bevers et al. 1995) and to assess the effectiveness of conservation planning (Nicholls et al. 1996; Akçakaya 2000).

Formally, we sought to minimize the highest extinction risk among the species:

$$\text{minimize } p_{\max}(x), \qquad \text{(objective 1)}$$

subject to a given budget B, where $p_{\max}(x)=\max_{i\in I} p_i(x)$, and I is the set of all i species $\{1,\ldots,n\}$. Therefore, $p_{\max}(x)\geq p_i(x)$ for all i species: the extinction risks of all other species will be lower than that of the umbrella species, the species most at risk. The umbrella species' extinction risk effectively acts as a threshold value that is minimized.

The umbrella species approach may minimize the expected loss of species when the best management action for the umbrella species alleviates the primary threat for all species. However, when driving habitat protection or reconstruction, it will result in only the habitat areas of the umbrella species being selected, unless, by chance, all the species are nested perfectly in their habitat preferences. Consequently, only a small proportion of the species under consideration is likely to have their extinction risk reduced.

Joint Probabilities of Extinction

The most readily translatable conservation objective is to maximize the chance that no extinctions occur (Hof & Raphael 1993; Hof et al. 1994; Bevers et al. 1995). This objective corresponds to minimizing the likelihood of being in the state where any species has become extinct over the management time frame. The objective is therefore to minimize the probability of one or more extinctions:

$$\text{minimize}\left(1-\prod_{i=1}^{n}\left[1-p_i(x)\right]\right). \qquad \text{(objective 2)}$$

High extinction probabilities are penalized because the objective value is equal to 1 if any one species faces certain extinction (Fig. 1). The objective returns more equitable extinction risks across species, as an increase in risk in

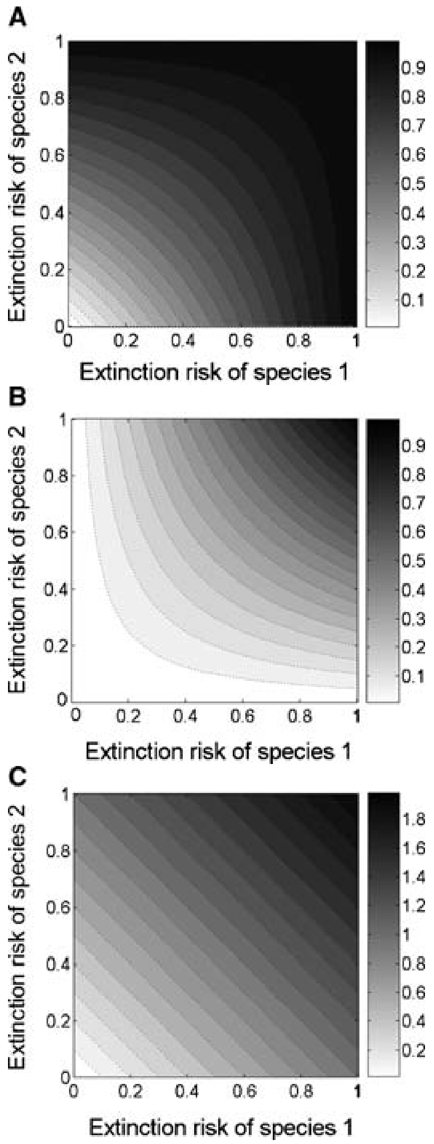

Figure 1. Possible combinations of extinction risks for two species and the subsequent objective value for three objective functions, assuming independent extinction probabilities: (a) the joint probability of one or more extinctions (objective 2); (b) the joint probability of all species going extinct (objective 3); and (c) the expected number of extinctions (objective 4). The shading becomes darker as the objective value across the two species increases. All values along a given shade are equivalent. For example, the objective value if minimizing the expected number of extinctions (c) is linear, two species with extinction risks of 0.5 is equivalent to one species having a risk of 0.1 and the other of 0.9. By contrast, if minimizing the probability of one or more extinctions (a), two species with a risk of 0.5 is equivalent to one species having a risk of 0.1 and the other of 0.72, whereas if minimizing the risk of all species becoming extinct (b), it is equivalent to one species being extinct and the other having an extinction risk of 0.25.

any species takes the probability closer to one or more species being extinct. With this objective, few species have very high or very low risks (Hof & Raphael 1993; Bevers et al. 1995), resulting in an approximately normal distribution across extinction risks (Hof & Raphael 1993).

An alternative joint probability, for a rather pessimistic conservation goal, is to minimize the probability that all species become extinct:

$$\text{minimize} \prod_{i=1}^{n} p_i(x). \qquad \text{(objective 3)}$$

When minimizing the probability of all species becoming extinct, the objective value only becomes high when all species have high extinction risks (Fig. 1). The value stays low even if some species become extinct as long as at least one species remains extant. This contrasts with minimizing the probability of one or more extinctions (objective 2), where the objective value is high if any species has a high risk.

The principal problem with the use of joint probabilities is that any correlations in extinction risks need to be considered explicitly (Sarkar et al. 2004; Wilson et al. 2005b). An assumption of independence can be made (Weitzman 1993; Hof et al. 1994; Williams & Araújo 2002), but extinction risks are likely to be correlated to some degree (Sarkar et al. 2004). When a given patch of habitat is lost, all species dependant on that area will experience some correlated increase in extinction risk. Species that interact will likewise suffer correlated changes in extinction risk. For example, the extinction of a predator is more likely if an important prey species becomes extinct, whereas species may have an increase in viability after the loss of a predator or competitor. Environmental stochasticity plays a large role in extinction risk (Sæther & Engen 2004; Frank 2005) and may add to correlations in risk, as will catastrophes such as drought or fire. Thus, an assumption of independence is unlikely to hold, potentially giving misleading results, as demonstrated below.

An alternative to assuming independence is to define the interdependence of extinction risks in some way (Solow et al. 1993; Witting et al. 2000). The measurement and parameterization of correlation in extinction risks are likely to be difficult and complex (Witting et al. 2000), making the use of joint probabilities problematic.

The second and much more feasible alternative is to use expectations, rather than joint probabilities, which are not beholden to the assumption of independence, and therefore do not produce the same anomalies (Sarkar et al. 2004; Wilson et al. 2005b).

Expected Number of Extinctions

Minimizing the expected number of extinctions corresponds well with the broad goal of maximizing biodiversity persistence. This objective has been used within an optimization framework (Hof & Raphael 1993; Bevers et al. 1995; Faith & Walker 1996; Williams & Araújo 2000; Camm et al. 2002) and in post hoc analyses to assess outputs of different reserve selection algorithms (Faith & Walker 1996; Araújo & Williams 2000). An analogous function, maximizing the mean persistence probability, has also been used (Williams & Araújo 2000; Williams & Araújo 2002). We minimized the expected extinctions by summing the extinction probabilities across all species:

$$\text{minimize} \sum_{i=1}^{n} p_i(x). \qquad \text{(objective 4)}$$

Here, the cheapest way to increase expected success will be taken because it is a greedy objective (Hof & Raphael 1993). All degrees of extinction risk are treated equally: a scenario that results in two species having the extinction probabilities of $p_1(x) = 0.1$ and $p_2(x) = 0.9$ has the same conservation value as a scenario with $p_1(x) = 0.5$ and $p_2(x) = 0.5$ (Fig. 1). Consequently, more expensive species may be sacrificed for species that are more cheaply and readily managed. This objective results in a roughly bimodal distribution of probabilities, with central tendencies for high and low extinction risks across the species, in contrast with the approximately normal distribution of extinction risks when minimizing the joint probability of one or more extinctions (Hof & Raphael 1993).

Relative Losses

Rather than minimizing the absolute risk of extinction, a comparative approach may be more meaningful. Species that gain the most benefit from conservation action can be emphasized (Metrick & Weitzman 1998) in accordance with a triage approach to conservation (McIntyre et al. 1992; Possingham et al. 2002). The compromise solution that most closely matches each species' preferred conservation scenario is sought by minimizing the increase in extinction risk from the best-case scenario.

Increase in the Expected Extinctions

A simple way to assess the relative change in risk is to minimize the increase in the expected extinctions: the difference between the extinction risk under the proposed plan, $p_i(x)$, and the extinction risk in the best-case scenario per species, given the budgetary constraints, $p_i(1)$:

$$\text{minimize} \sum_{i=1}^{n} \left(p_i(x) - p_i(1)\right). \qquad \text{(objective 5)}$$

Given that for a set budgetary constraint the values for $p_i(1)$ will remain constant, this objective can be rewritten as

$$\text{minimize} \left(\sum_{i=1}^{n} p_i(x) - \sum_{i=1}^{n} p_i(1) \right).$$

Therefore, although the objective has changed, the optimal strategy is the same as if the expected number of extinctions is minimized (objective 4). The linear treatment of changes in extinction risk means that an increase in risk from $p_i(1)$=0.01 to $p_i(x)$=0.10 is of equal benefit to an increase from $p_i(1)$=0.90 to $p_i(x)$=0.99 and to an increase from $p_i(1)$=0.46 to $p_i(x)$=0.55. Yet, in the first case the chance the species will become extinct has increased tenfold. In the second case, the persistence of the species is one-tenth as likely, whereas in the final case the relative increase in extinction and decrease in persistence probability are quite small.

Proportional Increase in Extinction Risk

Alternatively, the objective can be to minimize the sum of the proportional increase in extinction risk per species: the ratio of the extinction risks from the proposed scenario, and the best-case scenario under the same budgetary constraints. In this case, the objective function is

$$\text{minimize} \sum_{i=1}^{n} \frac{p_i(x)}{p_i(1)}. \qquad \text{(objective 6)}$$

For each species, the objective value is the proportional increase in its risk of extinction from the best possible scenario given the budget. For example, a species is four times more likely to become extinct if it has a best-case scenario extinction risk of $p_i(1)$=0.1 and an extinction risk under reserve scenario x of $p_i(x)$=0.4. Once added across the species, however, the objective value becomes a metric. Where there is no difference, the ratio is equal to 1, and this rises as the proposed action has an increasingly detrimental effect on the species.

Because the objective assesses the proportional increase, the lower the extinction risk for the best-case scenario, $p_i(1)$, the higher the objective value. Consequently, there is a strong emphasis on preventing species with low risk under ideal conservation conditions from becoming more threatened. For example, a species that goes from a best-case extinction risk of $p_i(1)$=0.1 to $p_i(x)$=0.4 makes an equal contribution to the objective as a species that goes from $p_i(1)$=0.01 to $p_i(x)$=0.04. This emphasizes not only the species that benefit most from conservation action but also those that are safest under that action. Although a triage approach argues that the entire budget should not be spent on species with little hope of success, the idea of abandoning high-threat species to their fate is abhorrent to many (McIntyre et al. 1992), precipitating the need for an alternative approach.

Emphasis on Relative Increases in Persistence and Relative Decreases in Extinction Probability

Another means of minimizing the difference from the best-case scenario is to abandon the equitable linear approach seen in objective functions 4 and 5 and place

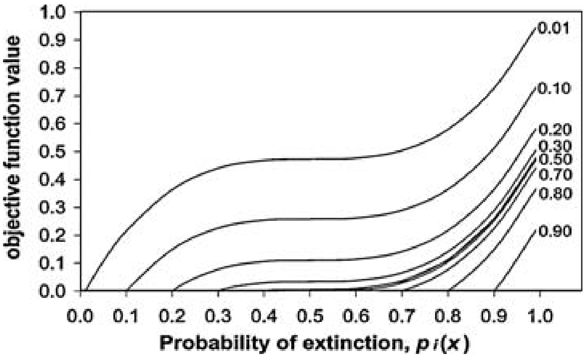

Figure 2. Objective function 7, minimizing the increase in extinction risk from the best-case scenario and emphasizing improvements for species with high persistence and extinction probabilities, for one species. On the x-axis is the extinction probability for species i *under reserve scenario* x, $p_i(x)$*, and on the y-axis is the objective function value for one species. The different curves and their labels refer to the extinction risk for the best-case scenario,* $p_i(1)$*, from* $p_i(1) = 0.01$ *(top line) to* $p_i(1) = 0.90$ *(bottom line). The curve is sigmoidal in the direction of both* $p_i(x)$ *and* $p_i(1)$*. The objective function values are scaled to lie between 0 and 1.*

emphasis on certain risk categories, although more selectively than with a ratio. There are many ways in which this might be done, depending on the conservation goal and which threat categories are deemed a priority. In this case, we assumed that the preference is to prevent highly threatened species from moving even closer to extinction while maintaining less threatened species as secure. To emphasize low- and high-threat species, we used a sigmoidal function from the second derivative of the logistic growth function (Fig. 2):

$$\text{minimize} \sum_{i=1}^{n} \left[\left(p_i(x) - \frac{4p_i(x)^2}{2} + \frac{4p_i(x)^3}{3} \right) - \left(p_i(1) - \frac{4p_i(1)^2}{2} + \frac{4p_i(1)^3}{3} \right) \right]. \qquad \text{(objective 7)}$$

If this objective function is applied to the previous example of a tenfold increase in extinction risk and a tenfold decrease in persistence probability, species that offer a greater return for the conservation effort are more selectively emphasized. This method can identify and emphasize threatened species provided they do not absorb the entire budget, instead allowing for prudent spending where more benefit may be gained for more and safer species. If species can be maintained at secure levels readily and cheaply, sustaining species assemblages and ecosystem function, then this is an important achievement for conservation and ecosystem management.

Table 2. The extinction risks per species for three hypothetical conservation scenarios.

Species	*Scenario A*	*Scenario B*	*Scenario C*
1	$P_1(a) = 0.10$	$p_1(b) = 0.20$	$P_1(c) = 0.15$
2	$P_2(a) = 0.55$	$p_2(b) = 0.45$	$P_2(c) = 0.35$
3	$P_3(a) = 0.80$	$p_3(b) = 0.75$	$P_3(c) = 0.85$

This objective function has no readily translatable meaning (such as the expected number of extinctions); rather, it is a metric for comparing options.

Example of the Outcomes of the Objective Functions

In the following example, we illustrate the implications of using different objective functions for setting conservation priorities. We considered a hypothetical case in which managers must choose among three alternative conservation scenarios. We assumed extinction risks are available for three species under each of the proposed scenarios (Table 2). The three species varied in the degree of threat they faced and in how they responded to the different scenarios. The best-case scenario values per species, $p_i(1)$, were given by the lowest extinction risks from these alternatives. For example, scenario A provided the best conservation outcome for species 1, with a best-case scenario extinction risk of $p_1(1) = 0.10$.

Using the objective functions described above, we combined the extinction risks and ranked the scenarios accordingly. The choice of scenario depended on the objective (Table 3), and the rankings varied greatly. Therefore, decision makers need to think carefully in selecting and defining the conservation goal.

The influence of the assumption of independence when using the objective functions that depend on joint probabilities was also important. We assumed varying degrees of independence of the species' extinction risks to assess its impact on the decision made. First, we assumed that the extinction risks were independent; that is, that the likelihood of one species becoming extinct was not related to the extinction risk of any other species. Second, we assumed that the extinction risks of two of the species were correlated, whereas the third remained independent. We arbitrarily decided that species 2 and 3 had correlated extinction risks: species 2 was more likely to become extinct if species 3 was, and vice versa, whereas the probability of their both becoming extinct was 30% higher than in the independent scenario. In the third example, we assumed that the extinction risks of all three species were nested: species 2 could only become extinct if species 3 was extinct, and species 1 could only become extinct if both species 2 and species 3 were extinct.

As we varied the degree of correlation in extinction risk, the probabilities of the different extinction states

Table 3. Ranking of hypothetical conservation scenarios based on the objective functions.

Objective function[a]	*Scenario* *A*	*B*	*C*
1. Umbrella species	2	1	3
2. Joint probability of one or more extinctions[b]	3	1	2
3. Joint probability of all extinct	1	3	2
4. Expected number of extinctions	3	2	1
5. Increase in the expected extinctions	3	2	1
6. Proportional increase in extinction risk	2	3	1
7. Relative losses: high persistence and high risk	1	2	3

[a] *Formulas provided in Table 1.*

[b] *The extinction risks are assumed to be independent across species.*

also changed (Table 4). In particular, the probability of no extinctions and the probability of all three species becoming extinct were different, affecting the resultant rankings of scenarios when using either of the objective functions based on joint probabilities (Table 5): the probability of one or more extinctions (objective 2) and the probability of all species becoming extinct (objective 3). By contrast, the expected number of extinctions remains unperturbed by assumptions of correlation in extinction risk (Sarkar et al. 2004; Table 4). In cases where the correlation in extinction risks is unknown, conservation scenarios cannot be confidently ranked using joint probabilities. The uncertainty and difficulties in understanding correlations in extinction risks across species mean joint probabilities should be used with extreme caution, if at all.

Conclusion

Objective functions within a decision-theoretic approach compel decision makers to explicitly state their conservation goals. Objectives that are a function of the extinction risk of multiple species use the common currency of population viability and address the goal of biodiversity persistence directly (Witting & Loeschcke 1993; Williams & Araújo 2002). They allow managers to look at the most cost-effective and transparent way of spending limited conservation funds, as opposed to more ad hoc traditional methods, whereby disproportionately large amounts may be spent on charismatic megafauna and highly threatened species with little chance of success (Metrick & Weitzman 1998; Possingham et al. 2002). The objective functions presented here did not disregard threatened species; rather, they allowed us to balance spending so that greater benefit could be gained by more species.

The objective functions we have presented translated broader conservation goals into explicit mathematical expressions, each representing alternative conservation ideals. The difficulty arises when there are many subtly different translations of overarching goals into mathematical objectives, as is the case from a broad goal such as maximizing the viability of species, and when these translations provide different answers. This will not always be the case. In many examples, the species' preferences will be nested, rendering the most appropriate conservation action evident and the ranking of alternative scenarios robust to changes in objective. However, when the species react differently to the alternative scenarios, the best option is not always obvious, and the objective can become crucial to the decision made. Different conservation decisions can result from using different currencies of viability, such as maximizing mean time to extinction versus minimizing extinction risk (McCarthy et al. 2005). It is disconcerting that even when using the same currency of extinction risk our management decision changed according to the way we set our objective. Because the choice of objective function matters and places emphasis on different threat levels, conservation decision makers need to consider and define their objectives carefully.

Bevers et al. (1995) argue that there are two conflicting goals in conservation: maximizing species richness

Table 4. Probabilities of different extinction states in conservation scenario B[a]**, assuming varying degrees of correlation in extinction risk among the three species.**

Probabilities of different states	*Degree of correlation in extinction risks* *independent*	*partly nested*[b]	*completely nested*
Probability of no extinctions[c] (objective 2)	0.11	0.19	0.25
Probability of one extinction	0.4475	0.3058	0.3
Probability of two extinctions	0.375	0.4155	0.25
Probability of three extinctions (objective 3)	0.0675	0.0878	0.20
Expected number of extinctions (objective 4)	1.4	1.4	1.4

[a] *Extinction risks per species are* $p_1(b) = 0.20$ *for species 1,* $p_2(b) = 0.45$ *for species 2, and* $p_3(b) = 0.75$ *for species 3.*

[b] *A 30% increase in the joint probability of species 2 and 3 becoming extinct.*

[c] *The probability of no extinctions,* $\prod_{i=1}^{n}\left[1 - p_i(x)\right]$, *is used in objective function 2 to minimize the probability of one or more extinctions:* $\left(1 - \prod_{i=1}^{n}\left[1 - p_i(x)\right]\right)$.

Table 5. Ranking of the hypothetical conservation scenarios assuming varying degrees of correlation in the species' extinction risks based on objective function 2, the joint probability of one or more extinctions, and objective function 3, the joint probability of all species becoming extinct.

Objective function	*Degree of dependence*	*Scenario A*	*Scenario B*	*Scenario C*
Probability of one or more extinctions (objective 2)	independent	3	1	2
	partly nested*	1	2	3
	completely nested	2	1	3
Probability of all species becoming extinct (objective 3)	independent	1	3	2
	partly nested*	2	3	1
	completely nested	1	3	2

**A 30% increase in the joint probability of species 2 and 3 becoming extinct.*

and equity. Maximizing the expected number of extant species, equivalent to minimizing the expected number of extinctions, can be interpreted as maximizing species richness, but it is not necessarily equitable. Some extinctions are permitted if compensated by low risks in other species (Hof & Raphael 1993; Bevers et al. 1995). Hof and Raphael (1993) and Bevers et al. (1995) therefore advocate joint probabilities of extinction and minimizing the highest extinction risk, our umbrella-species approach, as more equitable. The umbrella-species approach by definition ensures greater viability for species most at risk but potentially at the expense of the other species under consideration: two conservation scenarios of equal value for the umbrella species could have vastly different impacts on the other species. We demonstrated the difficulties in using joint probabilities of extinction, due to assumptions of independence, and advocate additive rather than multiplicative objectives. Additive functions such as objectives 6 and 7 allow decision makers to place emphasis on particular threat levels, provided the choice of function can be justified with an underlying conservation philosophy.

Other indices can be used to weight species value. For example, phylogenetic diversity can be included (Solow et al. 1993; Weitzman 1993; Williams 1998), as can species-specific weightings related to threat status (e.g., IUCN Red List). However, such a weighting could be somewhat arbitrary. Is a globally endangered species twice or three times as important as a regionally vulnerable species? This issue is further complicated by the extent of the distribution of the different species and the scale of the study region: some species may be endemic to the area under consideration, whereas the range of other species may extend far beyond. When assessing species of different phyla, and even kingdoms, how different species are from one another becomes an intractable question. The degree of the weighting would need to be well justified, or it could compromise the value of using an objective function in terms of providing a transparent and cost-effective distribution of conservation funds and effort.

A multiple-species planning framework, such as the one we present here, will be subject to many of the same limitations as a single-species process. Because not all species can be modeled, the choice of surrogates can be fraught with biases (Coppolillo et al. 2004). Although there is an extensive literature recommending the selection of a range of species from different taxonomic groups and representing sensitivity to different threatening process (Lambeck 1997; Fleishman et al. 2000; Coppolillo et al. 2004), the choice of study species is inevitably limited by the availability of information. As a consequence, the species included tend to be larger and more charismatic taxa, such as birds (Watson et al. 2001). Species, ecosystems, and threatening processes can inadvertently be excluded from the planning process. A combination of species modeling and ecosystem representation (Cowling et al. 1999) within a decision-theoretic approach may offer the best solution, ensuring the viability of particular species and coverage of habitat types and protection against key threatening processes (Carroll et al. 2003).

One of the greatest limitations in conservation planning, whether using reserve selection algorithms, expert opinion, or population viability analysis is uncertainty (Regan et al. 2002). Uncertainty in data, parameter estimation, and choice of model for each species may alter conservation decisions (Drechsler et al. 2003; Frank 2005; Wilson et al. 2005b), just as different assumptions about correlation of species' extinction risks change the ranking of scenarios. An advantage of using probabilities is that it is possible to explore the uncertainty surrounding them (Sarkar et al. 2004). Sensitivity analyses can be performed on the models used to predict extinction risk, assessing the impact of uncertainty in parameters and input data, and making the decision-making process more transparent to underlying assumptions (McCarthy et al. 2004). Objective functions can be used as part of a sensitivity analysis to test the robustness of multiple-species decisions, as should be done with a single-species conservation problem (Burgman & Possingham 2000; Drechsler et al. 2003).

The greatest benefit of assessing the adequacy of conservation plans though viabilities, captured in the multiple-species approach presented here, is the capacity to measure conservation success in a way that is readily understood, and in the basic currency of conservation: the risk of extinction (Williams & Araújo 2002). The extinction risk of species can also incorporate spatial and temporal dynamics, depending on the modeling method used (Akçakaya & Sjögren-Gulve 2000; Root et al. 2003).

Although the statement and clarification of conservation goals are a crucial part of planning for multiple species, the decision-making process should not be simplified into a single index (Failing & Gregory 2003). We still need to look at the impacts of conservation scenarios on the individual species that underlie the overall score and not use any tool blindly. The different answers that can result from using alternative objective functions mean that conservation goals must be carefully and clearly defined. It is not sufficient to state that we wish to "maximize biodiversity outcomes" if we are to achieve something concrete or measure success.

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