Conservation Biology

Contributed Paper

Effect of risk aversion on prioritizing conservation projects

Ayesha I.T. Tulloch,[*] Richard F. Maloney,[†] Liana N. Joseph,[*‡] Joseph R. Bennett,[*] Martina M.I. Di Fonzo,[*] William J.M. Probert,[*] Shaun M. O'Connor,[§] Jodie P. Densem,[†] and Hugh P. Possingham[*¶]

[*]ARC Centre of Excellence for Environmental Decisions, the NERP Environmental Decisions Hub, Centre for Biodiversity & Conservation Science, University of Queensland, Brisbane, Queensland 4072, Australia, email a.tulloch@uq.edu.au

†Science and Capability Group, Department of Conservation, Christchurch 8140, New Zealand

‡Wildlife Conservation Society, Bronx, NY 10460, U.S.A.

§Science and Capability Group, Department of Conservation, Wellington 6143, New Zealand

¶Department of Life Sciences, Imperial College-London, Silwood Park, Ascot, SL5 7 PY, United Kingdom

Abstract: *Conservation outcomes are uncertain. Agencies making decisions about what threat mitigation actions to take to save which species frequently face the dilemma of whether to invest in actions with high probability of success and guaranteed benefits or to choose projects with a greater risk of failure that might provide higher benefits if they succeed. The answer to this dilemma lies in the decision maker's aversion to risk—their unwillingness to accept uncertain outcomes. Little guidance exists on how risk preferences affect conservation investment priorities. Using a prioritization approach based on cost effectiveness, we compared 2 approaches: a conservative probability threshold approach that excludes investment in projects with a risk of management failure greater than a fixed level, and a variance-discounting heuristic used in economics that explicitly accounts for risk tolerance and the probabilities of management success and failure. We applied both approaches to prioritizing projects for 700 of New Zealand's threatened species across 8303 management actions. Both decision makers' risk tolerance and our choice of approach to dealing with risk preferences drove the prioritization solution (i.e., the species selected for management). Use of a probability threshold minimized uncertainty, but more expensive projects were selected than with variance discounting, which maximized expected benefits by selecting the management of species with higher extinction risk and higher conservation value. Explicitly incorporating risk preferences within the decision making process reduced the number of species expected to be safe from extinction because lower risk tolerance resulted in more species being excluded from management, but the approach allowed decision makers to choose a level of acceptable risk that fit with their ability to accommodate failure. We argue for transparency in risk tolerance and recommend that decision makers accept risk in an adaptive management framework to maximize benefits and avoid potential extinctions due to inefficient allocation of limited resources.*

Keywords: conservation decision making, cost-effectiveness analysis, management effectiveness, Project Prioritization Protocol, risk analysis, risk tolerance, threatened species, uncertainty

El Efecto de la Aversión de Riesgo sobre la Priorización de Proyectos de Conservación

Resumen: *Los resultados de la conservación son inciertos. Las agencias que toman decisiones sobre las acciones de mitigación de amenazas para salvar a determinada especie frecuentemente enfrentan el dilema de invertir en acciones con alta probabilidad de éxito y beneficios garantizados o escoger proyectos con un mayor riesgo de fracasar pero que pueden proporcionar beneficios mayores si son exitosos. La respuesta a este dilema yace en la aversión al riesgo de quien toma las decisiones – su negativa para aceptar resultados inciertos. Existe poca dirección en cómo las preferencias de riesgo afectan a las prioridades de inversión en la*

Paper submitted February 16, 2014; revised manuscript accepted June 26, 2014.

Conservation Biology, Volume 29, No. 2, 513–524

DOI: 10.1111/cobi.12386

conservación. Al usar una estrategia de priorización basada en la rentabilidad, comparamos dos estrategias: una estrategia de umbral de probabilidad de conservación que excluye a la inversión en proyectos con un riesgo de fracaso en el manejo mayor al nivel establecido, y una heurística con subestimación de varianza usada en la economía y que recuenta explícitamente la tolerancia de riesgo y las probabilidades del éxito o fracaso del manejo. Aplicamos ambas estrategias de priorización de proyectos en 700 de las especies amenazadas de Nueva Zelanda a lo largo de 8303 acciones de manejo. Tanto la tolerancia de riesgo de quienes toman las decisiones como nuestra opción de estrategia para lidiar con las preferencias de riesgo fueron conductores de la solución de priorización (p. ej.: la especie elegida para el manejo). El uso de un umbral de probabilidad minimizó la incertidumbre, pero se seleccionaron proyectos más costosos que con la subestimación de la varianza, la cual maximizó los beneficios esperados al seleccionar el manejo de especies con un mayor riesgo de extinción y un valor de conservación más alto. Al incorporar explícitamente las preferencias de riesgo dentro del proceso de toma de decisiones disminuyó el número de especies que se esperaban estarían a salvo de la extinción ya que una menor tolerancia de riesgo resultó en más especies excluidas del manejo, pero esta estrategia permitió a quienes toman las decisiones elegir un nivel de riesgo aceptable que encaja con sus habilidades para admitir el fracaso. Alegamos por una transparencia en la tolerancia de riesgo y recomendamos que quienes toman las decisiones acepten el riesgo en un marco de trabajo de manejo adaptativo para maximizar los beneficios y que eviten extinciones potenciales debidas a la asignación ineficiente de recursos limitados.

Palabras Clave: análisis de rentabilidad, análisis de riesgo, efectividad de manejo, especies amenazadas, incertidumbre, Protocolo de Priorización de Proyectos, tolerancia de riesgo, toma de decisiones de conservación

Introduction

Urgent decisions must be made to halt biodiversity declines with only partial understanding of management outcomes. To maximize efficiency of limited conservation budgets, resources should be prioritized toward the most cost-effective actions with the highest benefit-to-cost ratios (Bottrill et al. 2008; Wilson et al. 2009). Uncertainty in management outcomes and expected project benefits complicates decisions. One project may have low expected benefits but high certainty in achieving those outcomes, for example, a species close to recovery due to effective ongoing management action. Other projects may have high payoffs but low certainty in achieving them, for example, a species close to extinction for which recovery actions are poorly known. Resource managers implementing conservation decisions face an important dilemma: Should they invest in actions with high probability of success and guaranteed benefits or choose projects with a greater risk of failure that might provide higher benefits if they succeed?

Through applying risk analysis, decision makers weigh up the costs and benefits of investing in uncertain decisions by asking what the possible consequences of being right or wrong may be (Burgman 2005). Risk analysis is routine in financial decision making (Markowitz 1959) and increasingly incorporated in conservation decisions for managing fire (Maguire & Albright 2005), invasive species (Burgman et al. 2010), and fisheries (Little et al. 2014) and in spatial conservation planning under climate change (Ando & Mallory 2012). In conservation, the consequences of making a risky decision and being wrong include failing to adequately mitigate threats, wasting resources on an action that does not succeed, and damaging the reputation of the management organization. By taking a risk and investing in an uncertain yet cost-effective project that succeeds, managers may save funds they can spend on recovering other species or targeting other threats for mitigation. The 2 dimensions of calculating risk are the probability that the risk will materialize (i.e., the decision will fail to achieve intended outcomes) and its consequences, usually measured in terms of its expected benefits or utility (Burgman & Yemshanov 2013). Once feasible choices and associated risks have been assembled, the optimal mixture of choices that satisfies the management budget can only be generated after defining an objective and assessing the decision maker's tolerance to risk.

Risk tolerance is the degree to which a decision maker is willing or able to accept the possibility of an uncertain outcome in a decision (Harlow & Brown 1990). Personal and organizational risk tolerance have been widely studied for health-related (e.g., Van Houtven et al. 2011) and financial-planning decisions (Markowitz 1959; March & Shapira 1987). Risk tolerance has also been explored in relation to evolutionary fitness and foraging behavior (Real 1980; Stephens & Paton 1986) and more recently in environmental risk assessment; some choices, such as mining, carry high financial and organizational risk due to the potential impacts of catastrophes (Bugalla et al. 2012). Conservation priority-setting approaches have been developed that account for the risk of management failure by modifying the expected biodiversity benefits of an action based on the probability that the action will succeed (Nicholson & Possingham 2007; Joseph et al. 2009). Despite potential for risk preferences to alter conservation outcomes (Mouysset et al. 2012), the sensitivity of project priorities to different risk preferences has not been explored for species conservation. This is because most conservation priority-setting approaches are based on the assumption that managers are risk neutral. However, the literature suggests that many organizations charged with environmental management are risk averse (Stankey et al. 2003; Borchers 2005) (Supporting Information).

Cautious behavior in the face of uncertainties is the result of risk aversion, that is, a preference to avoid uncertain events regardless of their benefits in favor of certain outcomes with possibly lower payoff (Kimball 1993). For large publicly funded projects such as establishing national parks or managing catastrophic events such as wildfire, government agencies are punished severely for wasting taxpayers' money on failed projects (Fitzgerald 2002) and are likely to be risk averse (Lennox & Armsworth 2011). Risk aversion has traditionally led to a strict precautionary approach in many international and national legal systems (Supporting Information). The precautionary principle imposes a burden of proof on those who create potential risks and has been used to regulate environmental activities even if it cannot be shown that activities are likely to produce significant harm. However, in equally uncertain situations, such as securing conservation benefits on private land in agrienvironment or payment for environmental services schemes, or funding environmental entrepreneurism, some conservation agencies may be prepared to accept some level of risk if there is a chance of high returns (Gibbons et al. 2011) (Supporting Information).

By including the decision maker's level of risk aversion explicitly within a decision making framework, a decision can be selected that either maximizes expected returns for a given level of tolerable risk or minimizes risk for a given level of expected return (Markowitz 1959). The first objective sets an uncertainty level below which decisions are considered suboptimal (Polasky et al. 2011), whereas the second considers the uncertainty associated with different decisions and trades this off against expected outcomes (Mouysset et al. 2012). Trade-offs between risk and return mean that an action with high risk might still be considered if it provides high benefits (e.g., a reduction in the overall extinction risk of species). Both objectives are routinely explored in risk management for financial assets through expected utility analysis (Supporting Information) and modern portfolio theory (MPT) (Markowitz 1959), and complex mathematical optimization approaches have been developed (Björk et al. 2014). In expected utility theory, a decision maker seeks to maximize the expected value of some utility function $u(x)$, where x represents the return from a decision that might be received in money or goods and $u(x)$ represents the fitness of the decision, essentially the decision maker's happiness with the decision (Grechi et al. 2014). The degree of concavity of the utility function indicates the decision maker's level of risk aversion, with risk-averse decision makers always preferring a sure amount over a risky bet with the same expected value (Supporting Information). Most authors agree it is difficult to approximate this curve without a deep understanding of the true relationship between expected utility and returns (Starmer 2000). Perhaps due to this difficulty, risk aversion has only recently been explored in conservation prioritization in a spatial planning example of investing in wetland habitat conservation in the Prairie Pothole Region of the United States, for which risk diversification guided by MPT reduced uncertainty in outcomes by maximizing expected conservation returns for a given level of acceptable risk (Ando & Mallory 2012). These types of economic approaches can be complex to implement and explain to noneconomists. Conservation managers need a simple approach to explore how their willingness to accept risk might impact decisions, which can be communicated easily to funders and auditors.

For an example of species recovery in New Zealand, we applied 2 simple approaches to accounting for risk in decision making when prioritizing resource allocation to threatened species management. First, we set a probability threshold to select a portfolio of projects that excludes any project whose probability of failure is above an unacceptable threshold. Fixed thresholds quickly reduce the degree of uncertainty in funded projects, are easy to explain, and are commonly used in decision making (Huggett 2005; Martin et al. 2009), such as for classifying species extinction risk (IUCN & Mace et al. 2008). We define a probability threshold as the transition between a decision maker's optimal level of risk and the level at which risk exceeds acceptable levels. Uncritical use of thresholds can lead to ignoring management choices that might otherwise benefit from intervention (Bestelmeyer 2006). We therefore compared the threshold approach with a variance-discounting approach from the economic literature, which adjusts the probability of successfully managing a species by accounting for levels of unacceptable risk and probabilities of management failure.

Little guidance is available within national statutes or conservation policies regarding appropriate levels of risk aversion (Supporting Information). We therefore investigated the consequences of different scenarios of managers' risk tolerance with a cost-effectiveness approach to prioritization and solved the problem of selecting the most cost-effective set of species to manage given both a budget and a risk tolerance level. We examined the trade-offs between maximizing expected returns for a given level of unacceptable risk and minimizing the risk of a decision for a given level of return.

Methods

The Data Set

We used a data set of potential recovery projects for 700 of the most threatened New Zealand species (Townsend et al. 2008) that was developed using the Project Prioritization Protocol (PPP) (Joseph et al. 2009). This protocol informs priorities for allocating spending on threatened species management, following and based on the Noah's Ark framework (Weitzman 1998). Each species' project includes specific actions that, based on expert opinion, are necessary to ensure reasonable probability (95%) of species persistence over 50 years, costs, expected benefits, and feasibility (details in Joseph et al. [2009]).

The PPP

The PPP framework ranks the cost efficiencies of threatened species projects so that a set of species recovery projects can be selected under a given budget. The expected project efficiency, E, of species project i, is calculated as

$$E_i = \frac{B_i \times S_i \times W_i}{C_i}, \quad (1)$$

where the function for the total expected benefits of management is $B_i \times S_i \times W_i$, W_i is the species weight (based on taxonomic representation and distinctiveness, details in Bennett et al. [2014]), B_i is the biodiversity benefit, S_i is the feasibility (i.e., probability management of species i is successful [Supporting Information]), and C_i is the cost of all actions to manage species i. The biodiversity benefit B_i is calculated as the difference between the probability of the species persisting in 50 years with P_{1i} and without P_{0i} management (i.e., P_{1i} - P_{0i}), which represents the increase in the probability of species persistence under a recovery project compared with taking no action. We used these parameters to optimize the number of species projects selected for a given budget. The problem formulation for prioritization based on a knapsack approach is

$$\max \sum_{i=1}^{N} X_i B_i S_i W_i,$$

$$\text{subject to} \sum_{i=1}^{N} X_i C_i \leq budget, \quad (2)$$

where X_i is a decision variable for selecting project i from N projects that takes values of 0 or 1. Solving a knapsack problem identifies the optimal decisions X_i that are solutions to Eq. 2. Purchasing bodies (NGOs, state or national conservation organizations) can select projects that maximize total expected benefits $B_i S_i W_i$, where each project has a cost (takes up space in the knapsack) and delivers a benefit (biodiversity gains). The budget available determines the size of the knapsack. The PPP algorithm is freely available from A.I.T.T.

Evaluating PPP Outcomes

We used 3 performance criteria to define outcomes of PPP: total number of species managed for a fixed budget; representation among threat categories (through use of selection frequency of individual species in each New Zealand Department of Conservation threat category) (Townsend et al. 2008); and expected number of species safe from extinction. The expected number of safe species was the sum of the species likely to avoid extinction after a portfolio of species was chosen; therefore, this value includes managed and unmanaged species. Because each species has a likelihood of extinction and associated likelihood of persistence even without management, this value is not equal to the total number of managed projects—some unmanaged species will still survive, whereas some managed species are likely to go extinct. We calculated the expected number of safe species given a portfolio of selected species projects for management with

$$\text{safe species} = \sum_{i=1}^{N} (1 - X_i) P_{0i} + \sum_{i=1}^{N} X_i P_{1i} S_i + \sum_{i=1}^{N} X_i (1 - S_i) P_{0i}, \quad (3)$$

where X_i is the decision variable with a value of 1 or 0, depending on whether a species is selected for management. The first part of this equation ($\sum_{i=1}^{N} (1 - X_i) P_{0i}$) represents the expected number of species safe from extinction even though they were not managed. The second part ($\sum_{i=1}^{N} X_i P_{1i} S_i$) represents the expected number of species surviving because they were managed and the project was successful. The final part represents the expected number of species that survive despite management being unsuccessful ($\sum_{i=1}^{N} X_i (1 - S_i) P_{0i}$). This equation simplifies to

$$\text{safe species} = \sum_{i=1}^{N} P_{0i} + \sum_{i=1}^{N} X_i (P_{1i} - P_{0i}) S_i. \quad (4)$$

Incorporating Risk Aversion in Species Prioritization

Our problem was to find the best outcomes in terms of our performance criteria given risk preferences and budgetary constraints. We set up 3 scenarios (risk-neutral baseline, threshold to avoid risk, and variance discounting to accept risk) for considering risk aversion related to management failure in conservation and explored each with a different approach.

The baseline scenario represents traditional conservation prioritization approaches such as PPP, in which decision makers' risk aversion related to management failure is not considered. We ran the PPP with Eq. 2 to generate a list of species projects that could be achieved for an

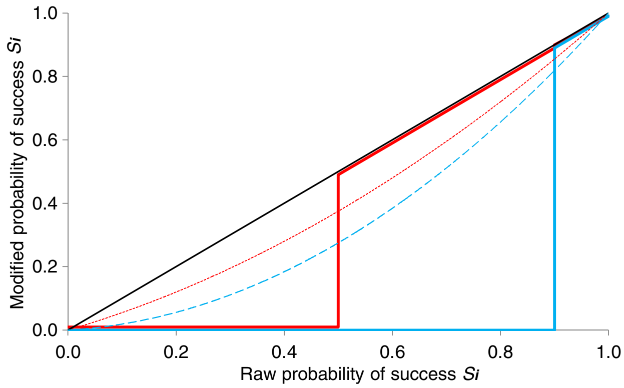

Figure 1. Relationship between raw probability of management success and the probability of management success modified using either a threshold exclusion approach or variance discounting (colored solid lines, probability threshold approach in which S_i *of projects below a given threshold is converted to zero; colored dashed lines, probability of success [*S_i*] modified with* $S_i - \alpha S_i[1 - S_i]$*); black solid line, raw data for* S_i*; blue lines, unacceptable risk level of 90% possible failure of the management action below which projects are considered risky by managers; red lines, unacceptable risk level of 50% possible failure of the management action below which projects are considered risky by managers.*

annual budget of NZ$30 million (the approximate 2012 operating budget of the NZ Department of Conservation [Department of Conservation 2013]).

In the threshold approach, managers predetermine a probability of success threshold below which projects are considered unacceptable for funding. We reran PPP iteratively with Eq. 2 and excluded all species projects with the success probability, S_i, lower than an acceptable probability threshold α (where $\alpha \in [0, 1]$) (Fig. 1). Thus, the PPP problem formulation changed to

$$\max \sum_{i=1}^{N} X_i B_i S_i W_i \ \text{s.t.} \sum_{i=1}^{N} X_i C_i \leq \text{budget and}$$
$$\text{s.t.} \quad S_i > \alpha \tag{5}$$

where all species projects must have a probability of success higher than the threshold α. We examined a range of α thresholds starting at risk tolerant projects (<10% probability of success excluded) and increasing in 10% increments of unacceptable risk up to 100% risk aversion (zero risk tolerance, only projects with 100% probability of success selected). Risk tolerance is typical of entrepreneurial nongovernmental organizations and adaptive management programs, whereas setting a high aversion threshold is typical of many government agencies that insist on a burden of proof before acting (Supporting Information).

In the variance-discounting approach, an adjusted feasibility value is calculated first and represents the difference between the expected outcome (probability of success) and the discounted variance of a probability (e.g., Everett & Schwab 1979; Real 1980):

$$\text{adjusted feasibility} = S_i - \alpha S_i (1 - S_i), \tag{6}$$

where $S_i(1 - S_i)$ represents the variance around a zero-one random variable in a Bernoulli trial and the coefficient α represents the level of unacceptable risk set by the decision maker, with α taking values between zero (risk neutral) and one (no risk accepted: risk averse). As α increases, the discounted variance around a decision increases and the adjusted feasibility decreases. We adjusted the benefit function from Eq. 2 by replacing S_i with our adjusted feasibility $[S_i - \alpha S_i(1 - S_i)]$ (Eq. 6 & Fig. 1) to account for uncertainty in the decision and the risk aversion of the decision maker:

$$\max \sum_{i=1}^{N} [X_i (S_i B_i W_i - \alpha S_i B_i W_i (1 - S_i B_i W_i))]$$
$$\text{s.t.} \sum_{i=1}^{N} X_i C_i \leq \text{budget}. \tag{7}$$

This approach does not automatically exclude any species. We reran the PPP iteratively with the variance discounting Eq. 7 for α values increasing in 10% intervals from $\alpha = 0.1$ to 1. The risk-neutral baseline scenario was based on the assumption of no risk aversion ($\alpha = 0$).

Trade-offs in Decision Making

We investigated the usefulness of the different risk approaches for achieving the alternative objectives of minimizing uncertainty and maximizing benefits for a given unacceptable risk level under an operating budget of NZ$30 million. We used cumulative probability density functions to explore how risk aversion decisions related to the risk of management failing affected the extinction risk of species through changes to the expected number of safe species. All data analyses were carried out in R version 2.15.1 (R Development Core Team 2012).

Results

Species Managed for a Given Budget

The variance-discounting approach allowed more species projects to be managed for the same budget than excluding species by probability thresholds (Table 1). Excluding species by thresholds resulted in a nearly 4-fold decrease in the total number of species projects selected, and costs increased exponentially from the baseline scenario which selected projects under no risk aversion (Fig. 2 & Table 1, Supporting Information). In

Table 1. Number of managed species and mean probability of management success for species sets prioritized under different risk aversion scenarios for a threshold approach compared with variance discounting that explicitly incorporates risk aversion into the benefit function.[a]

		Probability-threshold approach				*Variance-discounting approach*			
Unacceptable risk level (%)	*Risk aversion*	*Total species*	*Mean* S_i	*SD* S_i	*Selected projects with risk above the unacceptable threshold (%)*	*Total species*	*Mean* S_i	*SD* S_i	*Selected projects with risk above the unacceptable threshold (%)*
0	none	300	0.61	0.29	0	300	0.61	0.29	0
10	very low	300	0.61	0.29	0	300	0.61	0.29	1
20	very low	296	0.62	0.29	0	287	0.63	0.28	7
30	low	281	0.64	0.28	0	291	0.63	0.28	16
40	low	280	0.64	0.28	0	284	0.64	0.28	21
50	medium	242	0.71	0.24	0	283	0.65	0.28	31
60	medium	235	0.73	0.23	0	279	0.66	0.27	39
70	high	213	0.76	0.22	0	277	0.67	0.26	51
80	high	165	0.87	0.17	0	277	0.68	0.26	57
90	very high	128	0.91	0.15	0	273	0.69	0.27	70
100	very high	80	1.00	0	0	267	0.70	0.25	76

[a]*The project budget is NZ$30 million. The percentage of managed projects with probabilities of success below the level of unacceptable risk is also shown.* S_i, *probability of success.*

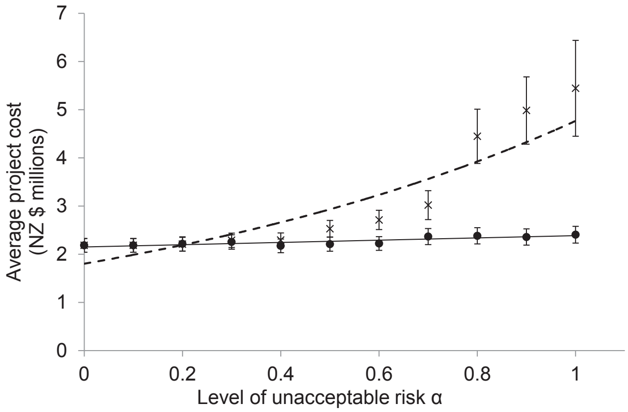

Figure 2. Relationship (mean, SD) between decision makers' level of unacceptable risk α and average project cost of managed species selected under a threshold approach to incorporating risk preferences excluding risky projects (crosses and dashed line, cost = 1.80e$^{0.9(threshold)}$, $R^2 = 0.84$, $P < 0.001$) compared with a variance-discounting approach accepting risky projects (circles and solid line, cost = 2.06α + 0.44, $R^2 = 0.86$, $P< 0.001$) decision making, in which the level of unacceptable risk describes the probability of failure of the project below which projects are considered risky by managers. lines, least squares regression.

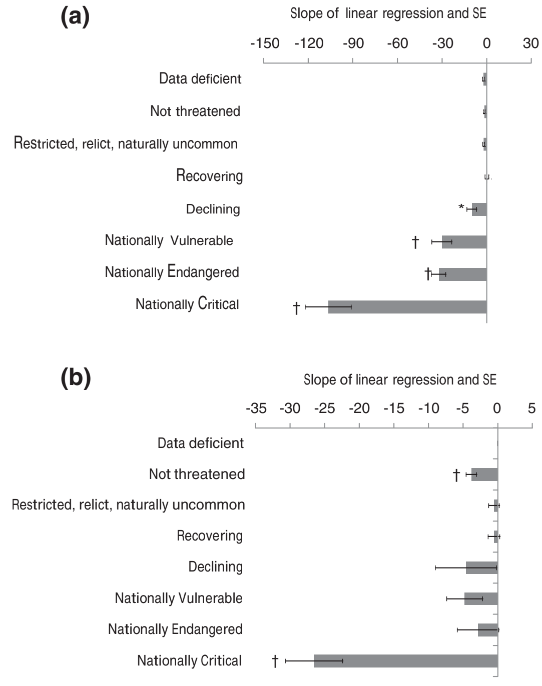

Figure 3. Results of application of increasingly unacceptable risk levels to selection of species projects with a NZ$30 million budget under 2 approaches: (a) probability thresholds (excluding species with probability of management failure below the unacceptable risk level) and (b) variance discounting (when risk aversion is incorporated into the benefit equation). Threat rank categories from New Zealand threat classification system 2002 and 2008. The x-axis scales differ ([a]significant at 0.05 level; [b]significant at 0.001 level).

comparison, with variance-discounting mean costs of species projects did not change significantly as risk aversion increased (Supporting Information) and there was a small but significant linear decline in the total number of species managed (Table 1 & Supporting Information).

Representation between Threat Categories

Increasing probability thresholds under an annual budget of NZ$30 million resulted in species from the 4 highest threat categories being excluded (including up to a third of nationally critical and endangered species at high thresholds of risk aversion; Fig. 3 & Supporting Information). The decline in the number of nationally critical species that could not be managed was much smaller under variance discounting and was not significant for all other threat categories, with the exception of a small decline in the selection of not threatened species (Fig. 3).

Expected Number of Species Safe from Extinction

The expected number of species safe from extinction declined rapidly under a threshold approach that avoided risk levels over 60%, but the number declined at a slower linear rate under variance discounting (Fig. 4a). The mean probability of extinction of species excluded from the funded pool ($1 - P_{0i}$) increased as risk aversion increased when a threshold approach was used (Fig. 4b). Species selected in the funding pool had declining values for the probability of extinction under no management relative to those excluded from management (Fig. 4b). At high levels of unacceptable risk, the threshold approach resulted in the extinction risk of excluded species being higher than that of selected species. In contrast, the mean probability of extinction given no management remained relatively stable under a variance-discounting approach, regardless of whether species were selected or excluded from the funding pool (Fig. 4b).

Trade-Offs in Decision Making

At low unacceptable risk levels, there was no difference between the mean probability of success of projects selected under either threshold exclusion or variance discounting (Table 1). At unacceptable risk levels >60%, the mean probability of success of the portfolio of species selected under variance discounting was below the level of unacceptable risk (Table 1) and

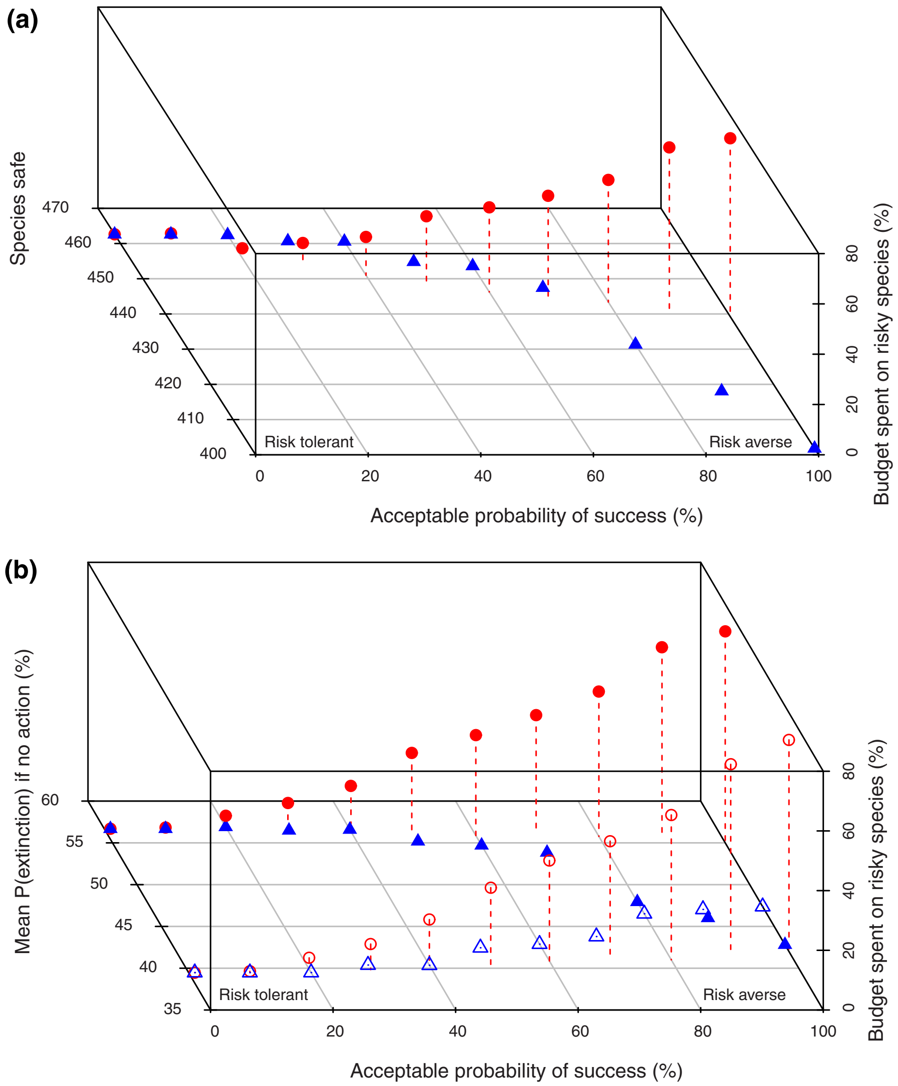

Figure 4. Effect of accounting for risk of management failure of species recovery projects on (a) expected number of species safe from extinction relative to the proportion of the budget spent on species projects that fall below the unacceptable level of risk (circles, variance-discounting approach incorporating risk explicitly into benefit function; triangles, probability threshold approach excluding species with probability of management failure below the unacceptable level of risk) and (b) mean probability of extinction of species (1 − P_{0i}) relative to the proportion of the budget spent on species projects that fall below the unacceptable level of risk under variance-discounting (circles) or threshold-exclusion (triangles) approaches (solid circles and triangles, extinction risk of species selected under different unacceptable risk levels; open circles and triangles, extinction risk of species excluded from prioritization).

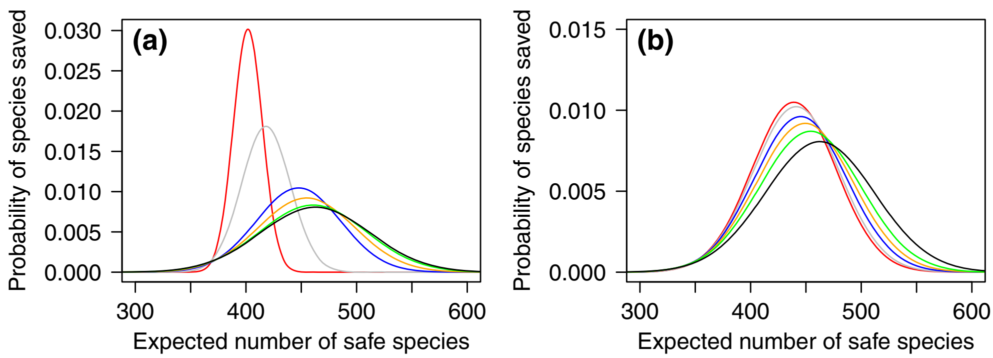

Figure 5. The change in probability distributions of the expected number of species safe from extinction (a) when thresholds of managers' levels of unacceptable risk are applied, below which species projects are excluded (black, no threshold; green, 30% threshold; orange, 50%; blue, 70%; grey, 90%; and red, 100%) and (b) for a variance-discounting approach with increasing α representing higher levels of unacceptable risk and corresponding aversion to the probability of management failure (black, zero alpha [no risk aversion]; green, 0.3; orange, 0.5; blue, 0.7; grey, 0.9; red, 1.0).

lead to an increasing proportion of risky projects being selected as risk aversion increased. With increasing risk aversion, threshold exclusion minimized uncertainty for a given level of unacceptable risk (Fig. 5), but fewer species projects were selected (Table 1 & Supporting Information). The variance-discounting approach maximized benefits; it consistently selected more species with a higher probability of being safe from extinction at levels of unacceptable risk over 50% than the threshold approach (Fig. 5 & Supporting Information).

Discussion

High uncertainty in management outcomes is an issue common to many conservation problems (Polasky et al. 2011) and leads to trade-offs in deciding whether to allocate funding to risky projects. Quantifying organizational risk tolerance levels, and incorporating these into decisions, is increasingly promoted (Maguire 1991). Despite this, there is little guidance on how to explore risk preferences in conservation decisions. We are the first to quantify trade-offs that arise if decision makers were to quantify risk tolerance and incorporate risk preferences in prioritization of species recovery. We incorporated aversion to the risk of management failure into prioritizing threatened species recovery projects based on cost effectiveness to determine when risk aversion might change conservation outcomes. When managers were risk tolerant (accepting uncertainty in outcomes of >50%), accounting for the risk of failure had little effect on overall outcomes (Table 1 & Fig. 4) because the cost-effectiveness approach to prioritization balanced the costs and benefits of different management choices. However, risk-averse decision makers who prefer levels of uncertainty of <50% faced a decline in the number of species that could be managed; loss of nationally critical, endangered, and vulnerable species (Fig. 3); and higher probability of extinction of unmanaged species (Fig. 4 & Supporting Information).

The ability to have greater confidence in conservation outcomes by accounting for risk aversion comes at a cost. Decisions that accept all risk (our baseline scenario) lead to funding risky projects with high benefits and low costs, which always appeared to optimize an objective of obtaining the greatest number of species for the least cost (Table 1). However, by not including the level of unacceptable risk in project prioritization, an unrealistic expectation of the number of species actually safe from extinction was created. High uncertainty around the number of safe species resulted from species projects with high probability of failure being selected. Accounting for risk aversion increased the certainty of selected species being safe from extinction (Fig. 5). This resulted in additional trade-offs because high-risk and low-cost species were replaced by species with lower risk but higher costs (Fig. 2).

By accounting for risk aversion in 2 different ways, we found that different objectives related to risk affected the outcomes of prioritizing species recovery. When the objective was to minimize uncertainty regardless of the payoff, threshold exclusion performed better than variance discounting because the most risky projects were never selected. Thresholds have appeal from a policy perspective due to simplicity, but by avoiding risk, thresholds could mean projects with potentially high payoffs are ignored. Logically, this results in an increasingly limited pool of species from which to choose, but also a mean probability of project success that is always higher than the threshold of unacceptable risk (Table 1). Managers wishing to maximize benefits to species can save more species from extinction by using an approach that incorporates risk aversion explicitly into decision making, such as the variance-discounting method (Figs. 4 & 5). This method could result in a mean probability of success below the level of unacceptable risk (but higher than if no risk aversion were included & Table 1), but it allows species that would fall under the probability threshold to be selected if they provide high benefits or are very cheap.

Our results support economic and policy studies that found the costs of a threshold approach that avoids or ignores low probability events can outweigh the benefits of simplicity and minimal risk (Camerer & Kunreuther 1989). We suggest that caution be taken with precautionary threshold-setting approaches, in particular if risk aversion is high. Sensitivity analyses showed that decision maker use of a threshold approach to minimize uncertainty under a probability threshold of 75% cost NZ$60 million annually to manage 270 species (Supporting Information). This is double the budget required to manage approximately the same number of species selected by incorporating the same level of unacceptable risk directly into PPP via variance discounting (Table 1). By accepting sometimes high proportions of risky cost-effective projects (Table 1), our variance-discounting approach avoids misallocation of scarce funding by trading off the benefits and costs of species that are safe from extinction against the certainty that outcomes might be achieved.

We analyzed risk aversion levels at intervals of 10%, approximating optimal risk aversion levels to explore the full range of consequences of tolerance to risk. In reality, decision makers probably have a limited range of acceptable risk, but are reluctant to state their level of risk aversion due to fear of reprisal if a project were to fail (Warah 2001). Because deciding on a specific threshold failure probability above which a project is unacceptable is arbitrary and difficult, we recommend using our variance-discounting approach to explore the trade-offs between species safe from extinction (this equates to the utility of the decision in the economic literature) and the proportion of the budget spent on risky species (Fig. 4). Decision makers can then easily explore and communicate to stakeholders the diminishing returns (in terms of safe species or mean extinction risk) as risk aversion increases. For species below the range of risk tolerance that are still selected for prioritization due to low costs and high benefits, risk mitigation measures might be required to justify spending. Alternatively, the cost of more risky decisions could be increased to include insurance against failure for species with high probability of failure that provide high potential benefits (Mumford et al. 2009).

We explored risk aversion as it relates to management failure, a form of financial risk, by combining the uncertainty around management effectiveness (a form of model uncertainty) with the likelihood of failure and the unacceptable levels of risk (Regan et al. 2002; Kasperski & Holland 2013). Model uncertainty acknowledges that there are competing hypotheses about how the ecological system (model) works, and the true model reflecting responses of species to threats and their management is unknown (Regan et al. 2002). To reduce this uncertainty, managers could implement adaptive management and monitoring to learn from a range of alternative management strategies which strategy optimizes recovery (McCarthy & Possingham 2007; Marescot et al. 2013). Uncertainty also exists in the probability of species persistence with and without action. In our analysis, a 95% probability of persistence secured species from extinction. By changing levels of acceptable species security, our method can be extended to account for a continuous range of extinction risk outcomes. In situations of expert elicitation such as PPP, uncertainty in the data can also arise due to subjective judgment and the risk of experts being wrong in parameter estimation. For the New Zealand PPP data set, values were assigned to B_i, S_i, and C_i through consultation with >100 threatened species experts. More recent applications of this protocol have also gathered information on the certainty of the experts in parameter estimation, which provides another level of uncertainty to account for (Carwardine et al. 2014).

Our approaches to incorporating risk into decision making frameworks for species prioritization are simple to explain, and we explored their use in management decisions for this reason. It is important that approaches developed for managers can be easily implemented and understood. The PPP has been used by New Zealand and Australian governments to prioritize funding for threatened species recovery projects. Although our feasibility methods were designed to be incorporated into this framework, they would be of use in any protocol that considers benefits, costs, and feasibility concurrently. Our variance-discounting approach is a heuristic, viewed in practice as a reasonable compromise between theoretical validity and operational simplicity. There is much discussion in the financial planning literature as to the relative merits of discounting compared with more complex risk diversification approaches (Everett & Schwab 1979; Ariel 1998). One barrier to implementing discounting rates is a lack of understanding of how adjusted feasibility values relate to true probabilities of management failure (Fig. 1). Despite this, discount rates are used in complex approaches for solving adaptive management problems such as stochastic dynamic programming (Marescot et al. 2013) and MPT (Ando & Mallory 2012). One challenge for species prioritization we did not address is spatial complementarity between strategies—the ideal suite of strategies protects as many species as possible without unnecessary redundancy in management actions (Tulloch et al. 2013). Finding the best set of strategies across species and space is difficult because there are an exponential number of combinations, which are computationally difficult to evaluate. We encourage future research to explore ways to incorporate these complex approaches into prioritization tools such as PPP, while maintaining transparency.

Accounting for risk preferences in decision making can help prioritize what to do because it allows exploration of the potential payoffs of willingness to accept failure. Weighing the costs and benefits of conservation decisions against their associated risk of failure in a risk analysis context allows the best decision to be made for a given level of risk aversion (Fig. 5). To maximize conservation returns whilst accounting for risk aversion, we recommend using our approach of incorporating risk aversion directly into the benefit function to explicitly account for decision makers' aversion to management failure. This approach is simple to use and transparent in the way it incorporates risk. It minimizes extinction of species, so the results are likely to be more acceptable to decision makers than a threshold approach because decision makers often view conservation effectiveness in terms of species lost or saved. Risk-averse managers focused on minimizing uncertainty regardless of returns risk ignoring highly endangered species. Regardless of whether managers seek to maximize benefits or minimize risk, risk aversion requires higher budgets to derive the same benefits as for risk tolerance. We suggest decision makers explore the impacts of a range of risk preferences on decision outcomes, as we have here, to investigate how personal and organizational tolerance to risk might (consciously or subconsciously) influence decisions.

Acknowledgments

We thank more than 100 threatened species experts for their support in parameterizing PPP in New Zealand, and I. Chades and V. Tulloch for discussions. This research was conducted with funding from the Australian

Government's National Environmental Research Program and the NZ Department of Conservation.

Supporting Information

Details explaining the methods behind PPP (Appendix 1), differences between economic approaches and our probabilistic approach to accounting for different risk preference levels in decision making (Appendix 2), examples of stated or indicated risk tolerances in government and non-government organizations (Appendix 2), results for different threat categories of sensitivity analyses exploring changes in unacceptable risk levels (Appendix 3), and further details of trade-offs in probability of success and cost when different approaches to incorporating risk preferences are applied to selecting species for recovery (Appendix 4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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