Stochastic dominance to account for uncertainty and risk in conservation decisions

Stefano Canessa*[1,2], John G. Ewen[1], Matt West[2], Michael A. McCarthy[2] and Terry V. Walshe[3]

[1]Institute of Zoology, Zoological Society of London, Regents Park, London, United Kingdom

[2]School of BioSciences, University of Melbourne, Victoria, Australia

[3]Australian Institute of Marine Science, Townsville, Qld, Australia

* Corresponding author

E-mails: SC: science@canessas.com; JGE: John.Ewen@ioz.ac.uk; MW: mwest@student.unimelb.edu.au; MAMC: mamcca@unimelb.edu.au; TVW: twalshe@unimelb.edu.au

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Abstract

Practical conservation normally requires making decisions in the face of uncertainty. Our attitude toward that uncertainty, and the risks it entails, shape the way conservation decisions are made. Stochastic dominance (SD), a method more commonly used in economics, can be used to rank alternative conservation actions by comparing the probability distributions of their outcomes, making progressive simplified assumptions about the preferences of decision makers. Here, we illustrate the application of SD to conservation decisions using the recovery plan for an endangered frog species in Australia as a case study. Stochastic dominance is simple and intuitively appealing for conservation decisions; its broader application may encourage conservation decision makers to consider probabilistic uncertainty in light of their preferences, which may otherwise be difficult to recognize and assess transparently. A better treatment of attitudes towards uncertainty and risk may help ensure rational decision making in conservation and remove potential causes of stakeholder conflict.

Introduction

Conservation biology aims to develop practical solutions to protect and restore natural systems and their functions (Soulé 1985). However, the predicted outcomes of conservation actions are typically uncertain, reflecting our incomplete knowledge of variable natural systems (Regan et al. 2002). While some actions will be successful in conserving systems, others can end up accelerating the same systems' demise. Consider for example the risk of introducing new diseases during species translocations (Cunningham 1996) or the potential damage from trophic cascades following eradication of invasive species (Bergstrom et al. 2009). Conservation decisions are routinely made in the face of such risks.

In expected utility theory (EUT: Von Neumann and Morgenstern 1944) decisions under probabilistic uncertainty are represented as *lotteries* which can lead to different outcomes, each with a given probability of occurring. Consider a hypothetical example in which managers need to choose between three conservation actions (Fig. 1a). Action A may preserve either two or six species with equal probability (p=0.5); action B may preserve either twenty or zero species with a probability of 0.2 and 0.8 respectively; action C is certain to preserve four species. Although actions with certain outcomes are unlikely in conservation, the use of a "certainty equivalent" assists in understanding risk attitude. Conservation decision makers will generally seek to maximize the number of species preserved; however, the action selected will also depend on their *risk attitude* (Pratt 1964). In this example, a risk-neutral decision maker will rate all actions equally: the expected outcome (the average of the possible outcomes weighted by their probabilities) is the same (four species). A risk-averse decision maker may choose action C to avoid the risk of a poor outcome. A risk-seeking decision maker may choose action B, preferring a chance of achieving the best possible outcome.

Within EUT the attitude of a rational decision maker can be represented by a *utility function*, which describes the satisfaction derived from different outcomes (Von Neumann and Morgenstern 1944). Rational decision makers will seek to maximize the utility of their decisions. In the above example, a risk-neutral decision maker has a linear utility function: they obtain the same utility from all actions with the same expected value (Fig. 1b). A risk-averse decision maker will obtain greater utility (satisfaction) by avoiding poor outcomes, so their utility function will be concave. A risk-seeking decision maker will have a convex utility function, reflecting their preference for highly positive outcomes (Fig. 1b).

A failure to account for such differences in risk attitude can lead to conflict and undermine conservation efforts, even when stakeholders may share the same broad conservation objective. This problem has been recognized by several authors (Duncan and Wintle 2008; Finnoff et al. 2007; Mace and Hudson 1999). However, risk attitude is rarely openly addressed in real-world conservation decision making (Greiner et al. 2009). Conservation decision makers may find it challenging to address personal values such as risk attitudes, which in turn involve ethical or "protected" values (Gregory et al. 2012), particularly where these are confounded with scientific judgment (Wilhere 2012). Defining utility functions can also be technically challenging (Durbach and Stewart 2009).

Here, we illustrate how stochastic dominance (SD; Levy 1998) can facilitate the explicit evaluation of risk in conservation decisions. This method is well known and frequently applied in economics (Levy 1992), but has rarely been applied in conservation, in spite of its potential value (Benítez et al. 2006; Knoke et al. 2008; Yemshanov et al. 2012). We illustrate the concepts and calculations of SD using a case study of threatened species management, and then discuss its advantages and limitations for conservation applications.

Stochastic dominance

Case study

Stochastic dominance is a decision-analytic tool that allows the preferential ordering of alternative actions with different probabilistic outcomes. To explain the key concepts and calculations of SD we consider the case of the endangered spotted tree frog *Litoria spenceri* in south-eastern Australia. Population declines have been linked to fungal infection (Gillespie 2014), habitat degradation (Gillespie 2002) and invasive species (Gillespie 2001). In-situ and ex-situ management actions have been proposed and implemented with the objective of downgrading the species to a less severe threat category (Gillespie and Clemann *in press*).

Here, we build on the example described in Canessa et al. (in press), focusing on a system of one extant population and one potential reintroduced population, where the objective was to maximize the overall probability of persistence at the end of a 20-year period. We consider five possible management strategies: (1) doing nothing, (2) full in-situ management of the existing population only, including control of weeds and introduced trout, (3) supplementation (*sensu* IUCN/SSC 2013) of the existing population by releasing captive-bred individuals, with full in-situ management, (4) reintroduction of captive-bred individuals to a new site with no further in-situ management and (5) reintroduction of captive-bred individuals to a new site and full in-situ management of all populations. Note this set of actions is not exhaustive and used here only for illustrative purposes.

The first step to formally assess risk is to predict the expected outcomes of each action and the relative uncertainty. We consider two scenarios with different levels of risk. The first scenario assumes that an ex-situ population has been successfully established and individuals are available for release (the actual current situation of the *L. spenceri* recovery plan). The second assumes that the ex-situ population has not yet been established; the probability of successful establishment (and production of animals for release) is estimated as 50%. This second scenario represented the decision problem at the beginning of the recovery plan, in the face of greater uncertainty.

During a workshop, we used a modified Delphi technique (see McBride et al. 2012 for details) to elicit the expected outcome (probability of persistence) for each of the five management strategies from a panel of experts. The distributions of outcomes for each action under the two scenarios are represented in Figure 2. Particularly in the second scenario (Fig. 2b), uncertainty is reflected by the considerable overlap among distributions.

First-order stochastic dominance

We can assess candidate actions in the face of uncertainty by comparing their cumulative distribution functions (CDFs). For any value x over the interval $[a,b]$, the CDF of a function $f(x)$ is the cumulative probability that the value of $f(x)$ is not greater than x. In other words, for a given action the CDF represents the probability that the outcomes of that action will be equal to or worse than a given value. For example, Figure 3a shows the CDFs of the distributions of outcomes for each action, obtained through numerical integration. The CDF for a persistence of 0.2 (x-axis) is 0.6 (y-axis) for Action 1 (doing nothing) and 0.2 (y-axis) for Action 2 (in-situ management only). Therefore, the probability of persistence is more likely to be greater than 0.2 when doing in-situ management than when taking no action. When the objective is to maximize the value of x (in this case species persistence), the rational choice is to select the action with the smallest CDF for a given value of x.

Assuming that greater utilities will always be preferred (more is better) implies that the utility function is non-decreasing and its first derivative u' is always positive. Under this assumption, Action A has *first-order stochastic dominance* (FSD) over Action B if:

$F_A(x) \leq F_B(x)$ for all x, and Eq. 1

$F_A(x) < F_B(x)$ for at least one value of x

where $F_A(x)$ and $F_B(x)$ are the CDFs of the utility functions for actions A and B respectively (Levy 1998). In other words, A dominates B at the first order when it has a smaller or equal CDF for any value of the objective x (in this case persistence): the CDF curve for A is always below or equal to the CDF curve for B, i.e. the two curves do not cross.

In the case of *L. spenceri*, the preference assumption is valid, since the recovery objective for the species is to maximize the probability of persistence. In the first scenario (known ex-situ success), the CDFs of the outcomes for all actions do not cross, and Action 5 (reintroduction paired with in-situ management), has first-order dominance over all other actions (Fig. 3a). Therefore, it represents the best action for any rational decision maker, and choosing it over other actions involves no risk.

Conversely, when ex-situ success is uncertain, the cumulative distribution functions for the selected actions cross in two cases (Fig. 3b): between Action 2 and Action 3, and between Action 4 and Action 5 (reintroduction without and with in-situ management respectively). The latter pair first-order dominates all other actions, which can therefore be discarded regardless of risk. The choice between Actions 4 and 5, however, involves risk attitude. Action 4 has a small chance of leading to greater persistence (the right-hand tail of the distribution), possibly reflecting less reliance on ongoing management; on the other hand, it also has a greater chance of a less positive outcome (the left-hand tail of the distribution). A risk-neutral decision maker would be indifferent to the level of risk, and would simply select the strategy with the highest mean persistence (0.63 and 0.61 respectively for reintroduction with and without in-situ management). For non-neutral risk attitudes, first-order SD cannot discriminate between these two actions; second-order SD must be explored instead.

Second-order stochastic dominance

Second-order SD requires knowledge of the general risk attitude of the decision maker; that is, whether they are risk-averse or risk-seeking.

For a risk-averse decision maker, the preference for minimizing risk implies a concave utility function with a second derivative that is always negative (Fig. 1b). Under this assumption of risk aversion, we can compare actions using the ascending integral of the CDF, $\int_a^x F(y)dy$. Action A has *ascending second-order stochastic dominance* over Action B if

$\int_a^x F_A(y)dy \leq \int_a^x F_B(y)dy$ for all *x*, and Eq. 2

$\int_a^x F_A(y)dy < \int_a^x F_B(y)dy$ for at least one value of *x* (Levy 1998).

If we consider the *L. spenceri* scenario in which the probability of ex-situ establishment is 0.5, the choice is now restricted to reintroduction with and without in-situ management of both source and reintroduced population, which dominated all other actions at the first order. The ascending integrals of the two CDFs do not cross, so again Action 5, reintroduction with in-situ management of both source and reintroduced populations, is the best action, since it has second-order dominance (Fig. 4a).

Conversely, a risk-seeking decision maker will prefer a higher probability of persistence even if it involves a greater risk: this attitude implies a convex utility function with a second derivative that is always positive. Under this condition, we can compare actions using the descending integral of the complementary CDF, $\int_x^b F'(y)dy$ (Wong & Li, 1999). For any value of *x*, this can be interpreted as the area above the CDF to the right of *x* (as opposed to the ascending integral in Eq. 2, which corresponds to the area under the CDF to the left of *x*). Action A has *descending second-order stochastic dominance* over Action B if

$$\int_x^b F'_A(y)dy \geq \int_x^b F'_B(y)dy \text{ for all } x\text{, and} \qquad \text{Eq. 3}$$

$$\int_x^b F'_A(y)dy > \int_x^b F'_B(y)dy \text{ for at least one value of } x.$$

For the *L. spenceri* example, the descending integrals of the CDFs for Action 4 and Action 5, reintroduction without and with in-situ management respectively, cross (Fig 4b). A risk-seeking decision-maker could not use SSD to discriminate between the two actions: a rational choice could be sought by exploring third-order SD (Whitmore 1970). This would require us to elicit the shape of the marginal utility function of the decision makers (Von Winterfeldt and Edwards 1986), which in turn corresponds to making assumptions about the third derivative of the utility function (Whitmore 1970). Such assumptions, and those for higher-order SD, may be difficult to interpret and apply to conservation decisions. More realistically, since the absolute difference between the two actions is marginal (Fig. 4b), the risk-seeking decision maker might simply be indifferent to the choice, or discriminate based on cost preferences instead.

Discussion

Uncertainty is a key element of conservation decision making (McCarthy 2014), and it can have different implications for decision makers depending on their risk attitude. However, conservation decisions under uncertainty often rely on expected values to choose among actions (mean outcomes; e.g. Canessa et al., in press) which do not immediately convey information about uncertainty or risk attitudes, assuming risk neutrality (Fig. 1a). An alternative approach in economics is to take the variance or standard deviation as a measure of risk, evaluating the mean-variance relationship for a defined degree of risk-aversion (Markowitz 1987; see Leskinen et al. 2006 for a conservation application). However, the variance is an adequate measure of risk only for a normal distribution, which is not likely to represent many conservation outcomes with skewed distributions. Conversely, stochastic dominance uses the full distributions of outcomes instead of one or two moments of the distribution.

In addition, a mean-variance analysis still requires a complete formulation of utility functions through indifference curves (Markowitz 1987). In this sense, possibly the greatest benefit of applying a non-parametric method such as SD to conservation decisions is in encouraging an explicit treatment of uncertainty and risk attitudes by reducing the elicitation burden on decision makers. Increasing orders of SD can be tested by progressively eliciting only limited information about the attitudes of decision-makers (Hildebrandt and Knoke 2011). Testing for FSD only requires an assumption of non-decreasing utility, and the calculation of CDFs for predicted outcomes. Full probability distributions can be obtained from quantitative analysis of empirical data or formal methods for the elicitation of expert judgment, as described in our example. For those non-dominated actions that cannot be discriminated at the first order, SSD adds an assumption about the general shape of the utility function (concave or convex).

In this sense, SD is advantageous since it does not require the definition of complete utility functions, which can be problematic for complex outcomes and non-monetary values. Moreover, since utilities represent the preferences of individuals, the extent to which they can be compared and aggregated is disputed (Eisenberg 1961). This can present a problem for conservation, where decisions often involve multiple stakeholders. For example, there may be little meaning in comparing the utility functions elicited from a group of stakeholders; however, the same group might reach a consensus about general risk-aversion, and such a simple definition is sufficient for a test of SSD. A general definition of risk aversion may also intuitively represent situations in which the preferences of decision-makers are dictated by mandates (such as institutional commitments to the precautionary principle). The main limitation to the use of SD is the difficulty of interpreting higher orders. Computational intensity may be limiting for large-dimensional problems with hundreds of competing actions; however, in our case numerical integration for SSD required only 2 minutes on a standard desktop computer (see Post 2003 for a more detailed discussion).

The specification of risk attitudes might be seen by some as an unnecessary complication. Pannell (2006) found “flat payoffs” to be predominant in agricultural production: the outcomes of different actions are similar enough that deviating from the mathematically optimal action (the one with the best expected outcome for the chosen criterion, such as expected value) will have little effect on utility across a considerable range of candidate actions, and risk attitudes will be essentially irrelevant. When verified for conservation decisions, as exemplified by our case study, the existence of flat payoffs reinforces the appeal of SD as a simple decision-support tool. Rather than discovering the irrelevance of uncertainty after eliciting utility functions, SD can be used to discriminate actions by simply comparing their cumulative distributions. This makes it applicable to any decision problem in which predicted outcomes can be expressed as distributions.

In our example, risk-averse and risk-seeking decision-makers would choose different actions; yet both would be rational under their respective attitudes. Unless the uncertainty surrounding outcomes is expressed and risk attitudes are approached transparently, such conflicts may not be resolved. Consider for example the debate concerning conservation triage (Joseph et al. 2008). Proponents of triage apply rational decision making to find the set of management actions that maximize the number of species conserved: this might imply that species with little chance of recovery may be less likely to be allocated resources (Bottrill et al. 2009).

Critics of triage argue that allocation of resources should allow for currently unforeseen breakthroughs that may eventually allow recovery (Jachowski and Kesler 2009), even if this means a greater chance of poorer overall returns by spreading resources over a larger set of species. It is possible that the two sides cannot agree because of fundamentally different risk attitudes. Tulloch et al. (2015) found that lower risk tolerance by managers would in fact reduce the total number of species protected, since efforts would concentrate on species in more imminent danger of extinction, which would however require greater concentration of resources. Future research could investigate risk attitudes in other areas of conservation (such as assisted colonization; Seddon et al. 2009), and explore violations of the assumption of rational decision making that is fundamental to expected utility theory and stochastic dominance (e.g. Tversky and Kahneman 1981).

Recognizing that decisions reflect utility, rather than expected outcomes alone, reveals that the definition of risk depends on preferences, and does not simply coincide with predicted outcomes. Importantly, the preferences that influence conservation decisions may go beyond those of conservation scientists or managers, also reflecting the values of the public or other stakeholders, adding to the challenge of explicitly defining subjective values. However, if such explicit definitions can be established, managers can then take full advantage of quantitative predictive tools that incorporate the full range of probabilistic uncertainty.

Stochastic dominance provides a relatively simple tool to assist conservation decisions in the face of uncertainty and risk. Its adoption could provide benefits to conservation managers at two levels. First, it requires definitions of uncertainty and risk that are transparent both quantitatively and semantically. Second, it allows a rigorous comparison of the predicted outcomes of possible actions with open recognition of risk.

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References

Benítez P.C., Kuosmanen T., Olschewski R., Van Kooten G.C. (2006) Conservation payments under risk: a stochastic dominance approach. *American Journal of Agricultural Economics* **88**, 1-15.

Bergstrom D.M., Lucieer A., Kiefer K. *et al.* (2009) Indirect effects of invasive species removal devastate World Heritage Island. *Journal of Applied Ecology* **46**, 73-81.

Bottrill M.C., Joseph L.N., Carwardine J. *et al.* (2009) Finite conservation funds mean triage is unavoidable. *Trends in Ecology & Evolution* **24**, 183-184.

Canessa S., Converse S.J., West M. *et al.* (in press) Planning for ex-situ conservation in the face of uncertainty. *Conservation Biology*.

Cunningham A.A. (1996) Disease risks of wildlife translocations. *Conservation Biology* **10**, 349-353.

Duncan D.H., Wintle B.A. (2008) Towards adaptive management of native vegetation in regional landscapes. pp. 159-182 in C. Pettit, W. Cartwright, I. Bishop, K. Lowell, D. Pullar, D.H. Duncan editors. *Landscape analysis and visualisation SE - 9, Lecture Notes in Geoinformation and Cartography* Springer Verlag, Berlin, Germany.

Durbach I.N., Stewart T.J. (2009) Using expected values to simplify decision making under uncertainty. *Omega* **37**, 312-330.

Eisenberg E. (1961) Aggregation of utility functions. *Management Science* **7**, 337-350.

Finnoff D., Shogren J.F., Leung B., Lodge D. (2007) Take a risk: preferring prevention over control of biological invaders. *Ecological Economics* **62**, 216-222.

Gillespie G.R. (2001) The role of introduced trout in the decline of the spotted tree frog (*Litoria spenceri*) in south-eastern Australia. *Biological Conservation* **100**, 187-198.

Gillespie G.R. (2002) Impacts of sediment loads, tadpole density, and food type on the growth and development of tadpoles of the spotted tree frog *Litoria spenceri*: an in-stream experiment. *Biological Conservation* **106**, 141-150.

Gillespie G.R., Clemann N. (*in press*) National Recovery Plan for the Spotted Tree Frog *Litoria spenceri*. Department of Environment and Primary Industries, East Melbourne, Victoria, Australia.

Gregory R., Failing L., Harstone M., Long G., McDaniels T., Ohlson D. (2012) *Structured decision making: a practical guide to environmental management choices*. John Wiley & Sons, Hoboken, NJ.

Greiner R., Patterson L., Miller O. (2009) Motivations, risk perceptions and adoption of conservation practices by farmers. *Agricultural systems* **99**, 86-104.

Hildebrandt P., Knoke T. (2011) Investment decisions under uncertainty—a methodological review on forest science studies. *Forest Policy and Economics* **13**, 1-15.

IUCN/SSC. (2013) *Guidelines for reintroductions and other conservation translocations. Version 1.0*. IUCN Species Survival Commission, Gland, Switzerland.

Jachowski D.S., Kesler D.C. (2009) Allowing extinction: should we let species go? *Trends in Ecology & Evolution* **24**, 180.

Joseph L.N., Maloney R.F., Possingham H.P. (2008) Optimal allocation of resources among threatened species: a project prioritization protocol. *Conservation Biology* **23**, 328-338.

Knoke T., Hildebrandt P., Klein D., Mujica R., Moog M., Mosandl R. (2008) Financial compensation and uncertainty: using mean-variance rule and stochastic dominance to derive conservation payments for secondary forests. *Canadian Journal of Forest Research* **38**, 3033-3046.

Leskinen P., Viitanen J., Kangas A., Kangas J. (2006) Alternatives to incorporate uncertainty and risk attitude in multicriteria evaluation of forest plans. *Forest Science* **52**, 304-312.

Levy H. (1992) Stochastic dominance and expected utility: survey and analysis. *Management Science* **38**, 555-593.

Levy H. (1998) *Stochastic dominance: investment decision making under uncertainty*. Kluwer Academic Publishers, the Netherlands.

Mace G.M., Hudson E.J. (1999) Attitudes toward sustainability and extinction. *Conservation Biology* **13**, 242-246.

Markowitz H.M. (1987) *Mean-variance analysis in portfolio choice and capital markets*. Blackwell, New York, USA.

McBride M.F., Garnett S.T., Szabo J.K. *et al.* (2012) Structured elicitation of expert judgments for threatened species assessment: a case study on a continental scale using email. *Methods in Ecology and Evolution* **3**, 906-920.

McCarthy M.A. (2014) Contending with uncertainty in conservation management decisions. *Annals of the New York Academy of Sciences* **1322**, 77-91.

Pannell D.J. (2006) Flat Earth Economics: the far-reaching consequences of flat payoff functions in economic decision making. *Review of Agricultural Economics* **28**, 553-566.

Post T. (2003) Empirical tests for stochastic dominance efficiency. *Journal of Finance*, 1905-1931.

Pratt J. (1964) Risk aversion in the small and in the large. *Econometrica: Journal of the Econometric Society* **30**, 122-136.

Regan H.M., Colyvan M., Burgman M.A. (2002) A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological Applications* **12**, 618-628.

Seddon P.J., Armstrong D.P., Soorae P. *et al.* (2009) The risks of assisted colonization. *Conservation Biology* **23**, 788-789.

Soulé M.E. (1985) What is conservation biology? *BioScience* **35**, 727-734.

Tulloch A.I.T., Maloney R.F., Joseph L.N. *et al.* (2015) Effect of risk aversion on prioritizing conservation projects. *Conservation Biology* **29**, 513-524.

Tversky A., Kahneman D. (1981) The framing of decisions and the psychology of choice. *Science* **211**, 453-458.

Von Neumann J., Morgenstern O. (1944) *Theory of games and economic behavior*. Princeton University Press.

Von Winterfeldt D., Edwards W. (1986) *Decision analysis and behavioral research*. Cambridge University Press, Cambridge, UK.

Whitmore G.A. (1970) Third-degree stochastic dominance. *The American Economic Review*, 457-459.

Wilhere G.F. (2012) Inadvertent advocacy. *Conservation Biology* **26**, 39-46.

Yemshanov D., Koch F.H., Barry Lyons D., Ducey M., Koehler K. (2012) A dominance-based approach to map risks of ecological invasions in the presence of severe uncertainty. *Diversity and Distributions* **18**, 33-46.

Figure legends

Figure 1. Panel (a) represents a hypothetical lottery with a decision between three alternative actions with different outcomes (numbers of species preserved) depending on success (with probabilities indicated by branch labels). Expected outcomes are calculated as the mean of possible outcomes weighted by their respective probabilities (e.g., for action A 6×0.5+2×0.5=4). Panel (b) represents the utility functions of risk-averse, risk-neutral and risk-seeking decision makers as indicated by labels.

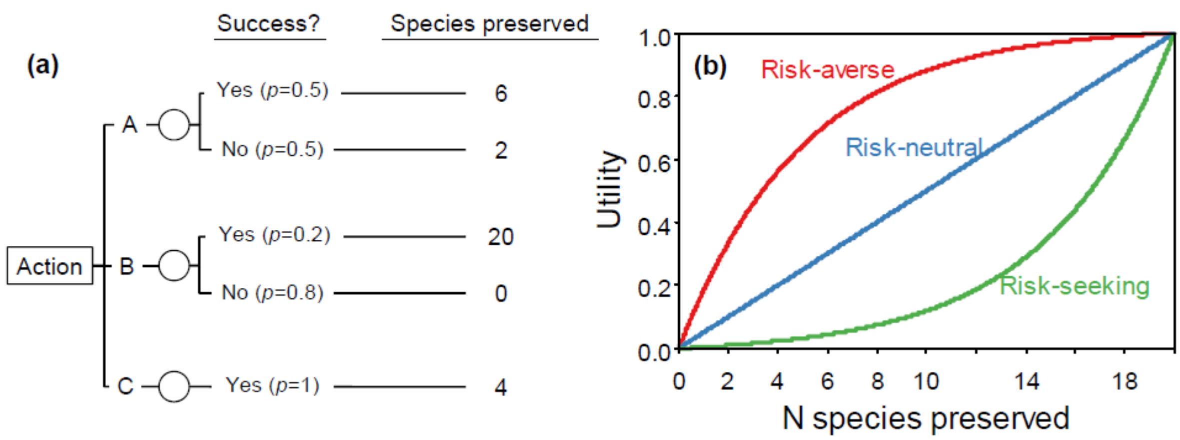

Figure 2. Elicited distributions of expected outcomes for the *Litoria spenceri* example, expressed as the probability of persistence of the species. The two panels correspond to the two uncertainty scenarios considered, respectively (a) known and (b) uncertain success of the ex-situ establishment phase. Actions indicate doing nothing (1), full in-situ management of the existing population only (2), supplementation of the existing population with full in-situ management (3), reintroduction to a new site with no further management (4) and reintroduction to a new site and full in-situ management of all populations (5).

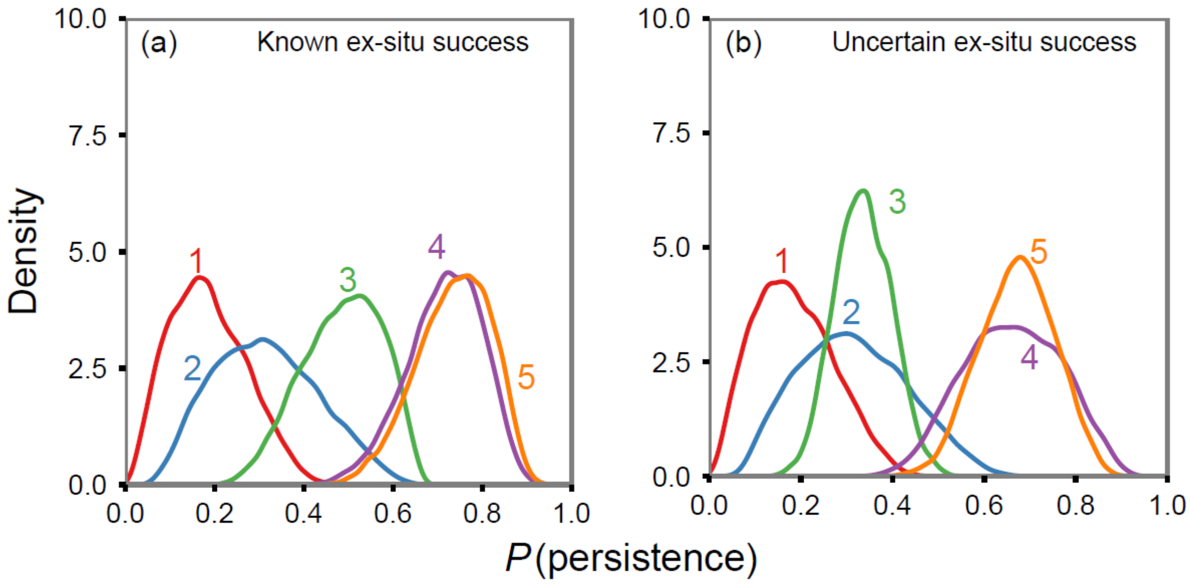

Figure 3. Cumulative density functions of the distributions of expected outcomes for *L. spenceri*, calculated by numerical integration of the distributions in Fig. 2. Where CDFs do not cross first-order stochastic dominance exists: for example, in panel (a) Action 5 dominates all other actions at the first order of SD.

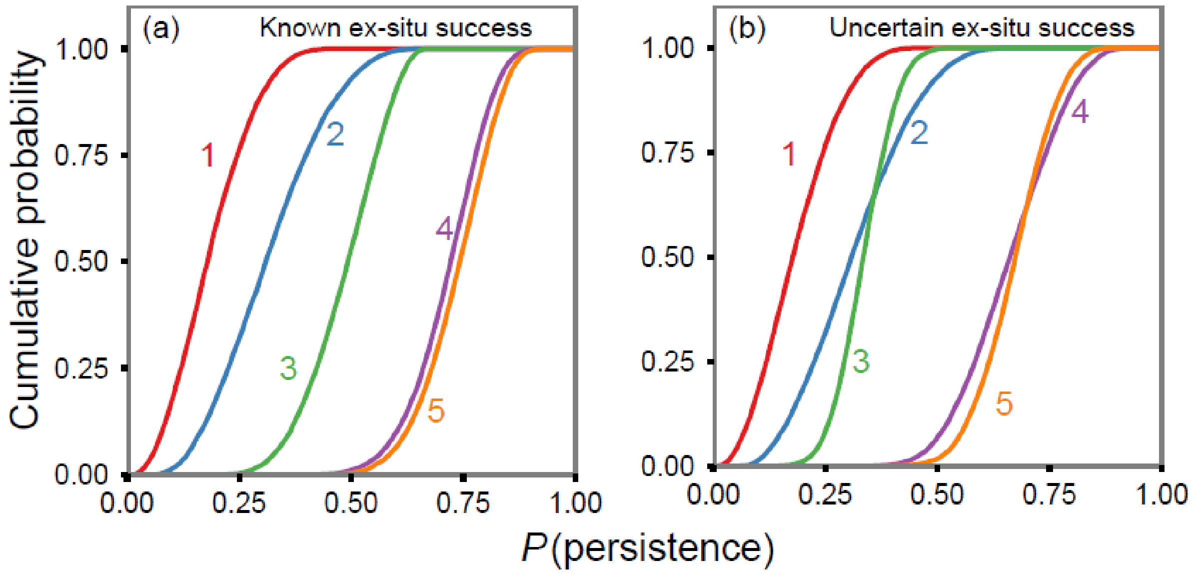

Figure 4. Second-order stochastic dominance for the outcomes for *L. spenceri*, in the scenario of uncertain success of the ex-situ establishment phase. Curves represent the integrals of the CDFs depicted in Figure 3b. Panel (a) and (b) show, respectively, ascending SSD for a risk-averse decision-maker and descending SSD for a risk-seeking decision-maker.