

1 **Stochastic dominance to account for uncertainty and risk in conservation decisions**

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23

24 **Abstract**

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

37

38 **Introduction**

39 Conservation biology aims to develop practical solutions to protect and restore natural  
40 systems and their functions (Soulé 1985). However, the predicted outcomes of conservation  
41 actions are typically uncertain, reflecting our incomplete knowledge of variable natural  
42 systems (Regan et al. 2002). While some actions will be successful in conserving systems,

43 others can end up accelerating the same systems' demise. Consider for example the risk of  
44 introducing new diseases during species translocations (Cunningham 1996) or the potential  
45 damage from trophic cascades following eradication of invasive species (Bergstrom et al.  
46 2009). Conservation decisions are routinely made in the face of such risks.

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

62 Within EUT the attitude of a rational decision maker can be represented by a *utility function*,  
63 which describes the satisfaction derived from different outcomes (Von Neumann and  
64 Morgenstern 1944). Rational decision makers will seek to maximize the utility of their  
65 decisions. In the above example, a risk-neutral decision maker has a linear utility function:  
66 they obtain the same utility from all actions with the same expected value (Fig. 1b). A risk-

67 averse decision maker will obtain greater utility (satisfaction) by avoiding poor outcomes, so  
68 their utility function will be concave. A risk-seeking decision maker will have a convex  
69 utility function, reflecting their preference for highly positive outcomes (Fig. 1b).

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

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

## 85 **Stochastic dominance**

### 86 *Case study*

87 Stochastic dominance is a decision-analytic tool that allows the preferential ordering of  
88 alternative actions with different probabilistic outcomes. To explain the key concepts and

89 calculations of SD we consider the case of the endangered spotted tree frog *Litoria spenceri*  
90 in south-eastern Australia. Population declines have been linked to fungal infection (Gillespie  
91 2014), habitat degradation (Gillespie 2002) and invasive species (Gillespie 2001). In-situ and  
92 ex-situ management actions have been proposed and implemented with the objective of  
93 downgrading the species to a less severe threat category (Gillespie and Clemann *in press*).

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

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

112 During a workshop, we used a modified Delphi technique (see McBride et al. 2012 for  
113 details) to elicit the expected outcome (probability of persistence) for each of the five  
114 management strategies from a panel of experts. The distributions of outcomes for each action  
115 under the two scenarios are represented in Figure 2. Particularly in the second scenario (Fig.  
116 2b), uncertainty is reflected by the considerable overlap among distributions.

### 117 *First-order stochastic dominance*

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

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

$$132 \quad F_A(x) \leq F_B(x) \text{ for all } x, \text{ and} \quad \text{Eq. 1}$$

$$133 \quad F_A(x) < F_B(x) \text{ for at least one value of } x$$

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

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

144 Conversely, when ex-situ success is uncertain, the cumulative distribution functions for the  
145 selected actions cross in two cases (Fig. 3b): between Action 2 and Action 3, and between  
146 Action 4 and Action 5 (reintroduction without and with in-situ management respectively).

147 The latter pair first-order dominates all other actions, which can therefore be discarded  
148 regardless of risk. The choice between Actions 4 and 5, however, involves risk attitude.  
149 Action 4 has a small chance of leading to greater persistence (the right-hand tail of the  
150 distribution), possibly reflecting less reliance on ongoing management; on the other hand, it  
151 also has a greater chance of a less positive outcome (the left-hand tail of the distribution). A  
152 risk-neutral decision maker would be indifferent to the level of risk, and would simply select  
153 the strategy with the highest mean persistence (0.63 and 0.61 respectively for reintroduction  
154 with and without in-situ management). For non-neutral risk attitudes, first-order SD cannot  
155 discriminate between these two actions; second-order SD must be explored instead.

156 *Second-order stochastic dominance*

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

159 For a risk-averse decision maker, the preference for minimizing risk implies a concave utility  
 160 function with a second derivative that is always negative (Fig. 1b). Under this assumption of  
 161 risk aversion, we can compare actions using the ascending integral of the CDF,  $\int_a^x F(y)dy$ .

162 Action A has *ascending second-order stochastic dominance* over Action B if

$$163 \int_a^x F_A(y)dy \leq \int_a^x F_B(y)dy \text{ for all } x, \text{ and} \quad \text{Eq. 2}$$

$$164 \int_a^x F_A(y)dy < \int_a^x F_B(y)dy \text{ for at least one value of } x \text{ (Levy 1998).}$$

165 If we consider the *L. spenceri* scenario in which the probability of ex-situ establishment is  
 166 0.5, the choice is now restricted to reintroduction with and without in-situ management of  
 167 both source and reintroduced population, which dominated all other actions at the first order.  
 168 The ascending integrals of the two CDFs do not cross, so again Action 5, reintroduction with  
 169 in-situ management of both source and reintroduced populations, is the best action, since it  
 170 has second-order dominance (Fig. 4a).

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



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

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

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

## 191 **Discussion**

192 Uncertainty is a key element of conservation decision making (McCarthy 2014), and it can  
193 have different implications for decision makers depending on their risk attitude. However,  
194 conservation decisions under uncertainty often rely on expected values to choose among  
195 actions (mean outcomes; e.g. Canessa et al., in press) which do not immediately convey  
196 information about uncertainty or risk attitudes, assuming risk neutrality (Fig. 1a). An  
197 alternative approach in economics is to take the variance or standard deviation as a measure  
198 of risk, evaluating the mean-variance relationship for a defined degree of risk-aversion  
199 (Markowitz 1987; see Leskinen et al. 2006 for a conservation application). However, the

200 variance is an adequate measure of risk only for a normal distribution, which is not likely to  
201 represent many conservation outcomes with skewed distributions. Conversely, stochastic  
202 dominance uses the full distributions of outcomes instead of one or two moments of the  
203 distribution.

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

216 In this sense, SD is advantageous since it does not require the definition of complete utility  
217 functions, which can be problematic for complex outcomes and non-monetary values.  
218 Moreover, since utilities represent the preferences of individuals, the extent to which they can  
219 be compared and aggregated is disputed (Eisenberg 1961). This can present a problem for  
220 conservation, where decisions often involve multiple stakeholders. For example, there may be  
221 little meaning in comparing the utility functions elicited from a group of stakeholders;  
222 however, the same group might reach a consensus about general risk-aversion, and such a  
223 simple definition is sufficient for a test of SSD. A general definition of risk aversion may also

224 intuitively represent situations in which the preferences of decision-makers are dictated by  
225 mandates (such as institutional commitments to the precautionary principle). The main  
226 limitation to the use of SD is the difficulty of interpreting higher orders. Computational  
227 intensity may be limiting for large-dimensional problems with hundreds of competing  
228 actions; however, in our case numerical integration for SSD required only 2 minutes on a  
229 standard desktop computer (see Post 2003 for a more detailed discussion).

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

241 In our example, risk-averse and risk-seeking decision-makers would choose different actions;  
242 yet both would be rational under their respective attitudes. Unless the uncertainty surrounding  
243 outcomes is expressed and risk attitudes are approached transparently, such conflicts may not  
244 be resolved. Consider for example the debate concerning conservation triage (Joseph et al.  
245 2008). Proponents of triage apply rational decision making to find the set of management  
246 actions that maximize the number of species conserved: this might imply that species with  
247 little chance of recovery may be less likely to be allocated resources (Bottrill et al. 2009).

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

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

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

271

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276

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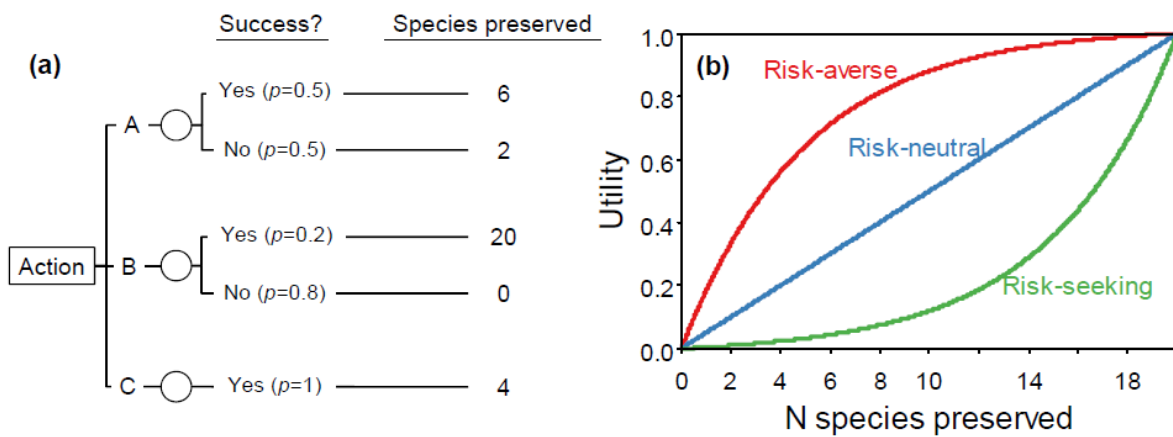
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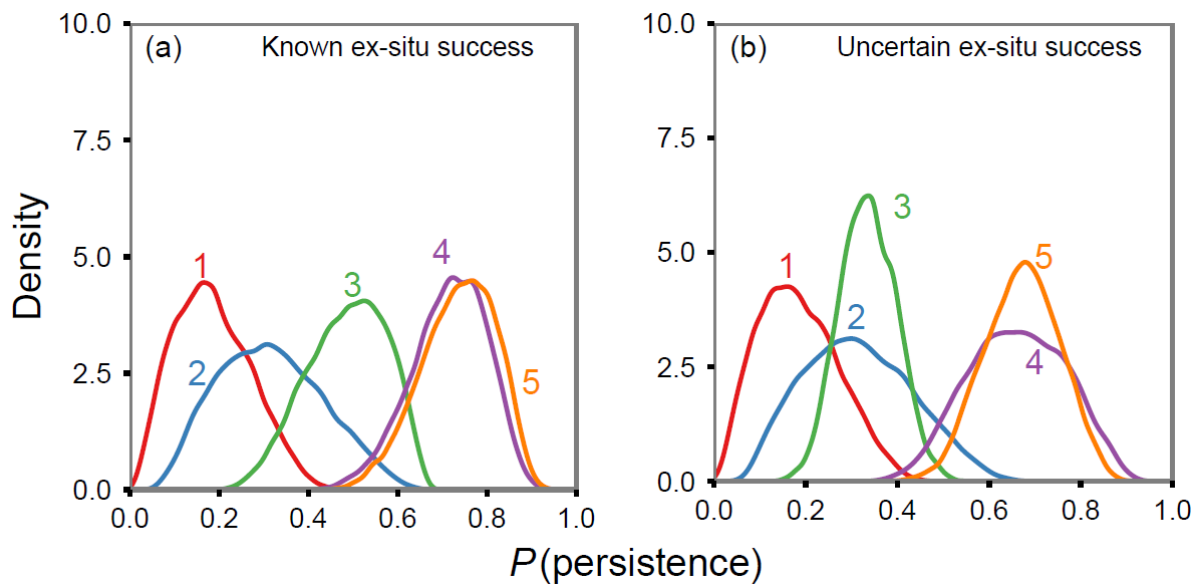
368 **Figure legends**

369 **Figure 1.** Panel (a) represents a hypothetical lottery with a decision between three alternative  
 370 actions with different outcomes (numbers of species preserved) depending on success (with  
 371 probabilities indicated by branch labels). Expected outcomes are calculated as the mean of  
 372 possible outcomes weighted by their respective probabilities (e.g., for action A  
 373  $6 \times 0.5 + 2 \times 0.5 = 4$ ). Panel (b) represents the utility functions of risk-averse, risk-neutral and  
 374 risk-seeking decision makers as indicated by labels.



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383 **Figure 2.** Elicited distributions of expected outcomes for the *Litoria spenceri* example,  
384 expressed as the probability of persistence of the species. The two panels correspond to the  
385 two uncertainty scenarios considered, respectively (a) known and (b) uncertain success of the  
386 ex-situ establishment phase. Actions indicate doing nothing (1), full in-situ management of  
387 the existing population only (2), supplementation of the existing population with full in-situ  
388 management (3), reintroduction to a new site with no further management (4) and  
389 reintroduction to a new site and full in-situ management of all populations (5).  
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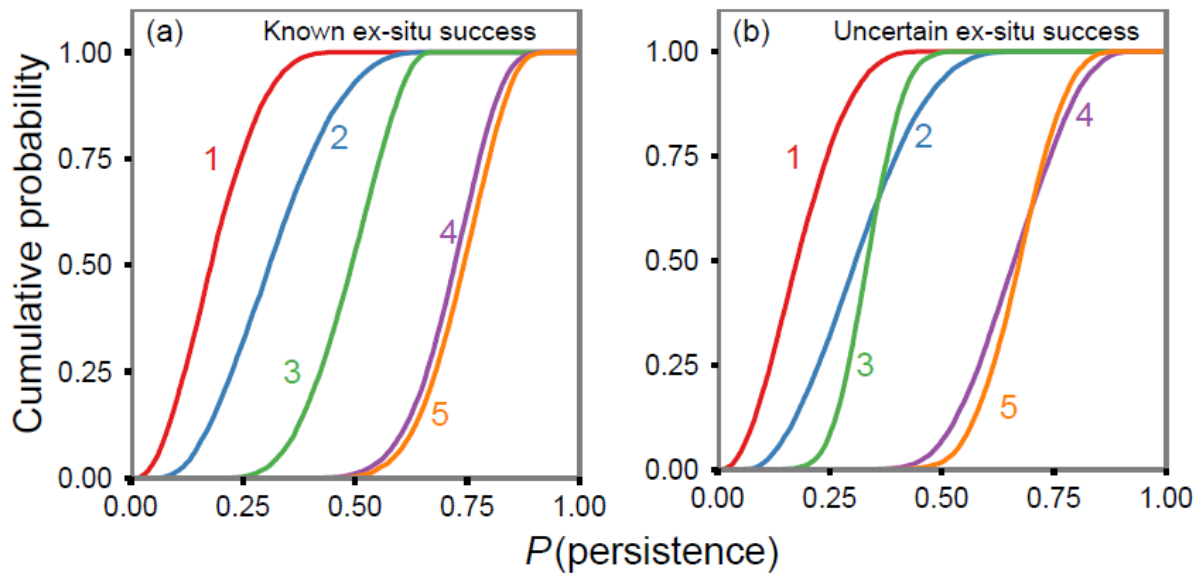
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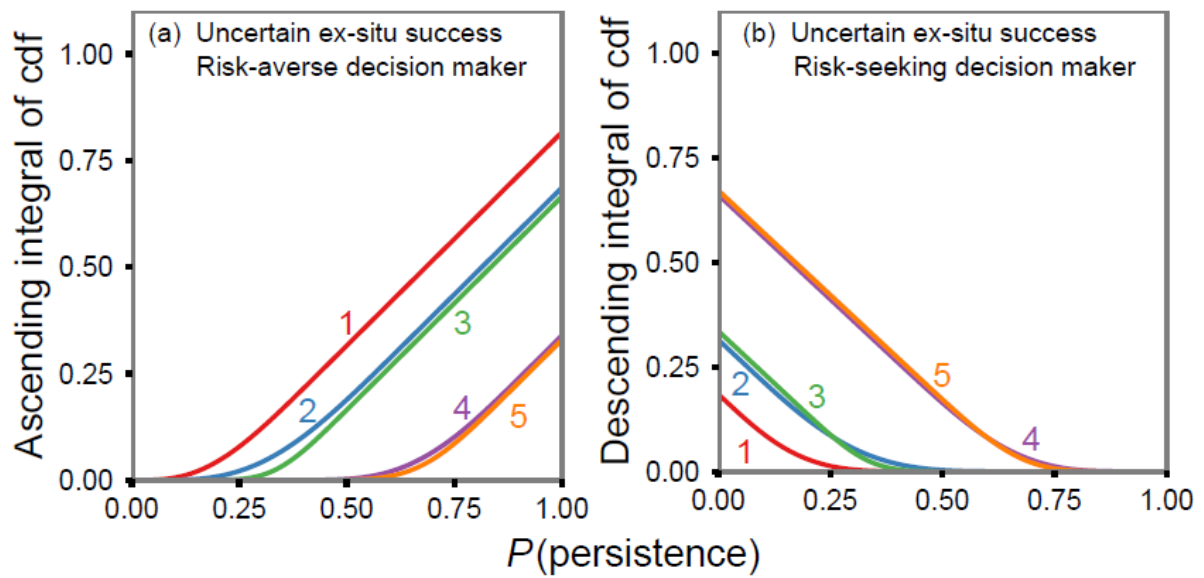
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397 **Figure 3.** Cumulative density functions of the distributions of expected outcomes for  $L$ .  
398 *spenceri*, calculated by numerical integration of the distributions in Fig. 2. Where CDFs do  
399 not cross first-order stochastic dominance exists: for example, in panel (a) Action 5  
400 dominates all other actions at the first order of SD.



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



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