



# Making structured decisions for reintroduced populations in the face of uncertainty

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## Abstract

Structured decision-making (SDM) has become popular in natural resource management but has been underused in reintroduction programs. We illustrate how conservation managers can use SDM to guide management decisions after initial reintroduction, when data are still limited and uncertainty around vital rates estimates is high. In 2013, the hihi (*Notiomystis cincta*), an endangered New Zealand forest bird, was reintroduced to Bushy Park (BP), a managed conservation reserve. High post-release mortality in females led to the population remaining small after 2 years, raising the question of whether more females should be released. We built a model to evaluate three management alternatives, including no further translocation and translocations of 15 additional females (from the only possible source population) in either 2015 or 2016. The fundamental objectives identified were to maximize the number and persistence of female hihi in BP, minimize the impact on the source population, and minimize costs. Our decision analysis incorporated uncertainties in parameter estimation, model selection, and demographic stochasticity. It produced distributions of final scores for each management alternative based on population projections for both the BP population and source population, and objective weights assigned by stakeholders. Although the distributions of final scores overlapped greatly, the “no translocation” alternative was largely stochastically dominant over other management options, that is, it was clearly the best choice in most projections and the choice was ambiguous in the remaining projections. The decision was also unaffected by variation in stakeholder values. Although the underlying modeling was complex, the output provided a simple visualization of outcomes that allowed the recovery group to make an informed decision (no further translocation) that fully considered the uncertainties.

## KEYWORDS

hihi, *Notiomystis cincta*, objective weights, population management, population model, population reinforcement, reintroduction, structured decision-making

## 1 | INTRODUCTION

Reintroductions are conducted around the world to aid in threatened species recovery and restoration of ecosystems

(Soorae, 2018). The new science of reintroduction biology has led to increasing ability to predict the fates of reintroductions (Seddon, Griffiths, Soorae, & Armstrong, 2014). However, this research is rarely embedded within the

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management decisions taken for reintroduced populations (Taylor et al., 2017). Ideally, predictions of outcomes under alternative management actions are compared against objectives to select the best one.

Reintroductions necessarily involve a series of decisions, both before and after the reintroduction takes place. Decisions require alternatives, and each management alternative may have its pros and cons and different level of uncertainties. To decide which management alternative is appropriate in a particular situation, structured decision-making (SDM) may be used. SDM requires defining the problem, identifying fundamental objectives, developing a set of possible management alternatives, and then comparing and selecting the best of these alternatives based on predictions of achieving objectives and how much these objectives are valued (Hammond, Keeney, & Raiffa, 1999). The rationale of SDM is to decompose complex problems into smaller steps, overcome the common human errors in judgment in each of these steps, and combine to produce a rational choice.

This approach has become popular in natural resource management decisions (Gregory et al., 2012; Gregory & Keeney, 2002) but has been underused in reintroduction biology (Taylor et al., 2017). The effectiveness of SDM in reintroduction decisions has recently been highlighted in management of endangered whooping cranes (*Grus Americana*), helping managers decide whether or not releasing captive-reared chicks would help to recover the Florida non-migratory population (Converse, Moore, Folk, & Runge, 2013). In this case, predictions suggested that the release of three cohorts of captive-reared chicks per year for 10 years with an immediate start was the best choice among many alternatives for achieving the specified management objectives (Converse, Moore, Folk, & Runge, 2013). Additional examples where SDM has assisted in reintroduction decision-making include selection of post-release supplementary feeding of reintroduced hihi *Notiomystis cincta* on Kapiti Island, New Zealand (Ewen, Soorae, 2014; Ewen, Walker, 2014); choosing a best reintroduction strategy that maximized the number of adults at the destination population without reducing the source population in bull trout *Salvelinus confluentus* (Brignon, Peterson, Dunham, Schaller, & Schreck, 2017); and developing a state-based reinforcement strategy for flatwoods salamanders (*Ambystoma cingulatum* and *Ambystoma bishopi*) (O'Donnell et al., 2017).

A benefit of SDM is that the underlying decision analytic tools can take full account of uncertainty. Uncertainty permeates most components of reintroduction decisions; linguistic uncertainty compromises our meaning at all decision steps causing confusion within management teams, whereas aleatory and epistemic uncertainties mean our knowledge of

systems and how they will respond to management are never known with certainty. In fact, many reintroduction decisions are made based on poorly defined objectives (Ewen, Soorae, 2014; Ewen, Walker, 2014) and simple deterministic predictions of the consequences of management alternatives that do not incorporate uncertainty. The latter implies that the parameters are estimated without error, and the optimal decision is clear as long as the different objectives are weighted within a representative utility function. Incorporating uncertainty in the estimations of management outcomes may change the perception of the utility of alternatives and certainly makes decisions more transparent (Gregory et al., 2012). For example, Canessa et al. (2016) advocated such an approach for deciding whether to initiate a captive breeding program for threatened species management. Representing uncertainty through a decision tree allowed a more nuanced representation of how captive breeding could assist in species recovery and had the benefit of clearly linking uncertain outcomes directly on stated objectives (Canessa et al., 2016). It should go without saying that the best management decision not only depends on the best mean outcome predicted but also on the probability distributions of possible outcomes.

In this study, we demonstrate how SDM may be used in making decisions about population reinforcement, one of the most common problems in reintroduction biology that is used to increase population size and its viability (Hardy, Hull, & Zuckerberg, 2018). It is typically hoped that post-release monitoring will identify whether population reinforcement is required and will improve reintroduction outcomes. However, even with good post-release data, predicting the dynamics of a reintroduced population can be challenging due to uncertainty (Bar-David, Saltz, Dayan, Perelberg, & Dolev, 2005). Moreover, the potential benefits of translocation have to be weighed against the impact on the source population. Thus, our goal was to develop a decision support tool for population reinforcement that accounted for various types of uncertainty and incorporated multiple objectives about both the source and destination populations.

## 2 | METHODS

### 2.1 | Species and management context

Hihi are small (ca. 40 g) endemic New Zealand forest birds. They are sexually dimorphic, feed on fruits, nectar and invertebrates, and nest in cavities of mature trees. Before European colonization, hihi were found all over the North Island and on some offshore islands. However, by the 1880s, they had become extinct everywhere except Te Hauturu-o-Toi (Little Barrier Island) due to habitat loss and

predation by introduced mammals (Boyd & Castro, 2000). Hihi have been translocated to 10 additional sites since 1980, of which six remain extant, and where ongoing management recommendations are provided by the Hihi Recovery Group (HRG) (Ewen, Renwick, Adams, Armstrong, & Parker, 2013).

## 2.2 | The decision problem

In March 2013, the HRG approved reintroduction of hihi to Bushy Park (BP), an 87-ha lowland rainforest remnant surrounded by a fence (Xcluder™ “kiwi”) designed to exclude introduced mammals. The 44 birds released were from Tiritiri Matangi (TM) Island, which is currently considered the only possible source population. BP is a community-based conservation project that has a team of volunteers who help to monitor birds and maintain feeders and nest boxes. The BP population declined over the first 2 years due to poor initial survival of the reintroduced females (only four of 21 females survived the first 6 months), but modeling projections suggested that this was due to transient effects of the translocation (cost of release effects; Armstrong et al., 2017) and that more stable site based vital rates would allow the population to persist (Panfylova, Bemelmans, Devine, Frost, & Armstrong, 2016). However, uncertainty in these projections and an underlying belief that more birds would improve reintroduction outcomes led the BP Trust to propose reinforcing the population with additional birds.

The HRG therefore needed to make a recommendation on whether to support a reinforcement or not. At the 2014 annual HRG meeting, group members worked through an SDM process to solve this decision. Four fundamental objectives were identified that were related to three objectives driving hihi recovery nationally (Ewen et al., 2018) but modified for the context of the BP Trust request. These included: (a) Maximize the size of the source population (related to national objective of maximizing number of hihi); (b) Maximize persistence of the destination population (related to national objective of maximizing number of hihi); (c) Maximize size of the destination population (related to national objective of increasing public appreciation); and (d) Minimize cost (related to national objective of minimizing cost) (Table 1; Panfylova, 2015). Although the first two objectives relate to the same national objective, the group believed it was important to distinguish between the source and destination population because they are valued differently by different group members.

After the objectives were specified the group developed four management alternatives: (a) status quo, meaning continue ongoing management and monitoring but no further translocation for at least 2 years; (b) translocation of an additional 15 juvenile females from TM Island in March 2015;

**TABLE 1** Fundamental objectives and measurable attributes for decision whether to translocate additional hihi from Tiritiri Matangi (TM) Island to Bushy Park (BP)

Objectives	Measurable attributes/uncertainty
Maximize size of source population (TM)	Number of female hihi in Sep 2016, 95% CRI
Maximize size of destination population (BP)	Number of female hihi in 10 years, 95% CRI
Persistence of destination population	Whether >0 female hihi at BP in 10 years
Minimize cost	Amount of funds spent on translocation

Abbreviation: CRI, credible interval.

(c) delaying the follow-up translocation to March 2016, and (d) relocating hihi from BP to another reserve. Discussion of these alternatives resulted in the fourth alternative being immediately rejected. The two translocation alternatives were set at a small number of juvenile females harvested from the source population given a risk averse stance to larger harvests. The third alternative similarly represented a more cautious approach from some in the group who wanted to *wait-and-see* the outcome of the original translocations before committing more birds. Rather than simply waiting before deciding, the HRG explicitly developed this idea as an alternative with the choice judged best by its consequences.

To estimate the consequences of each alternative for the first three objectives, we modeled the existing demographic data for both the source and destination population to obtain probability distributions for our performance metrics. The value of the cost objective was known and represented the amount of funds needed for the translocation project, thus it was the same for the first two alternatives and cost 0 for the “no translocation” alternative. Finally, we elicited objective weights from stakeholders based on these projections, and combined this information to produce distributions of weighted scores for each alternative.

## 2.3 | Projecting the impact of harvesting the source population

To inform the first objective, we developed a model to simulate the probability distribution of the number of breeding-age females in the source population in the 2016 breeding season (September) following either no harvest, or a possible March 2015 or March 2016 harvest (the three alternatives considered). The short-term projection we use here reflected the managers' wish to support harvesting as long as the source population remained about the same size in the

subsequent breeding season, while also avoiding complications concerning future (annual) decisions about harvesting this population.

We used OpenBUGS (Spiegelhalter, Thomas, Best, & Lunn, 2010) code based on a spreadsheet model that has been used since 2005 to guide harvesting from TM hihi population (Armstrong & Ewen, 2013). The model is female-only (females are the sex likely to limit population growth) and incorporates uncertainties related to demographic stochasticity and parameter uncertainty. Although Ewen, Thorogood, and Armstrong (2011) detected subtle density dependency in hihi reproductive success and sex ratio, the estimated effect size was trivial in relation to the manipulation in density in this study thus was not included in the model. The OpenBUGS harvesting model models fecundity (first year and older females) and survival (juvenile and adults) based on parameter estimates (and associated standard errors) using data collected from 1996 to 2004 (Armstrong & Ewen, 2013). These demographic rates have been stable so far and given accurate projections. The initial numbers of first-year birds and older birds were estimated using data from bi-annual surveys conducted up to September–October 2014.

## 2.4 | Projecting population dynamics at destination site

To inform objectives two and three (Table 1), we used a female-only population model developed by Panfylova et al. (2016). The model was coded in OpenBUGS and predicted population dynamics over 10 years based on four main parameters: mean fecundity of first-year and older females, juvenile survival, and adult survival. Data to inform this prediction model were collected during post release monitoring in BP from March 2013 to March 2015 (see Panfylova et al., 2016 for details). The model incorporated uncertainty related to demographic stochasticity and parameter estimation. Model selection uncertainty was reflected in the parameter uncertainty through model averaging. We modified the OpenBUGS code to incorporate the three management alternatives (Appendix S1) and derived whether the population persisted after 10 years (objective 2) and the estimated number of breeding females plus uncertainty in these estimates (objective 3) for each. This code may also be run from R using R2OpenBUGS or R2JAGS packages (Sturtz, Ligge, & Gelman, 2005; Kéry & Schaub, 2011).

## 2.5 | Evaluating trade-offs

We used the Simple Multi-Attribute Rating Technique (SMART; Barron & Barrett, 1996) to evaluate the trade-offs between the three alternatives. This technique requires

assigning *weights*, which are the measure of how stakeholders value fundamental objectives given their differences among alternatives. We identified how each of the four fundamental objectives were important by asking HRG members to assign weight to each of the objectives. Eight HRG members were involved and included two employees of the New Zealand Department of Conservation, two scientists and two representatives from each of the two conservation sites (BP and TM Island). Each person was provided with the modeling results arranged in a consequence table (Table 2) and explained that they should weight the relative value of each objective shifting from the lowest to the highest values among the three 95% credible intervals (CRIs). We asked each person to assign 100 points to the most important objective, and weight other objectives relative to the most important one in a range between 0 and 100. These values were then normalized so they summed to 1, giving normalized weights ( $W_j$ ) (Table 3).

SMART also requires transformation of all objective scores to *normalized objective scores*, so they are all standardized on the same scale between zero and one, with 0 given to the worst objective outcome across the alternatives and 1 given to the best outcome. To account for uncertainty in our OpenBUGS model, we assigned 0 to objective outcomes with the lowest value of the 5th percentile of the 99% CRI across all 3 alternatives; while 1 was the highest value of the 95th percentile of the 99% CRI across all 3 alternatives.

$$N_{i,j} = \frac{S_{i,j} - \min_i (S_{i,j})}{\max_i (S_{i,j}) - \min_i (S_{i,j})}, \quad (1)$$

where  $N_{i,j}$  is the *normalized objective score* under alternative  $i$  in relation to objective  $j$ , and  $S_{i,j}$  refers to the original scores (Converse, Moore, & Armstrong, 2013; Hyde, 2006).

These were then used to obtain the final score for each alternative ( $F_i$ ), which is given by

$$F_i = \sum_j W_j * N_{i,j}, \quad (2)$$

and shows the relative preference for each alternative under a particular set of outcomes.

We incorporated these weighting calculations into the OpenBUGS code simulating the dynamics of the TM and BP populations, and used this to produce a probability distribution for the final score under each alternative. To assess sensitivity to stakeholder weights, we did the calculations both using average stakeholder weights and using each of the eight sets of stakeholder weights separately.

**TABLE 2** Consequence table for decision whether to translocate additional hihi from Tiritiri Matangi (TM) Island to Bushy Park (BP), showing performance of each alternative with respect to each objective

Objectives	Goal	Objective scores (mean with 95% CRI) <sup>a</sup>		
		Translocation 2015	Translocation 2016	No translocation
Maximize size of source population (TM)	Max	55.1 (31–88)	58.4 (33–93)	68.2 (42–103)
Maximize size of destination population (BP)	Max	83.0 (1–100)	82.1 (1–100)	79.7 (0–100)
Persistence of destination population (yes = 1, no = 0)	Max	0.982 (0–1)	0.990 (0–1)	0.979 (0–1)
Minimize cost	Min	NZD 13,200	NZD 13,200	0

Abbreviation: CRI, credible interval.

<sup>a</sup>Credible intervals, scores for first three objectives are projections from stochastic population models incorporating uncertainty in parameter estimation.

**TABLE 3** Objective weights representing scores of importance assigned by stakeholders (eight Hihi recovery group members in this study)

Objectives	Objective weights								Extreme weights		Averaged weights
	1	2	3	4	5	6	7	8	Max	Min	
Maximize size of source population (TM)	0.34	0.13	0.37	0.24	0.23	0.37	0.23	0.16	0.13	0.37	0.26
Maximize size of destination population (BP)	0.39	0.74	0.51	0.61	0.65	0.51	0.64	0.74	0.39	0.74	0.60
Persistence of destination population	0.26	0.13	0.10	0.14	0.11	0.10	0.12	0.09	0.09	0.26	0.13
Minimize cost	0.01	0.00	0.03	0.01	0.01	0.02	0.01	0.01	0.00	0.03	0.01

Abbreviations: BP, Bushy Park; TM, Tiritiri Matangi.

## 3 | RESULTS

### 3.1 | Population projections

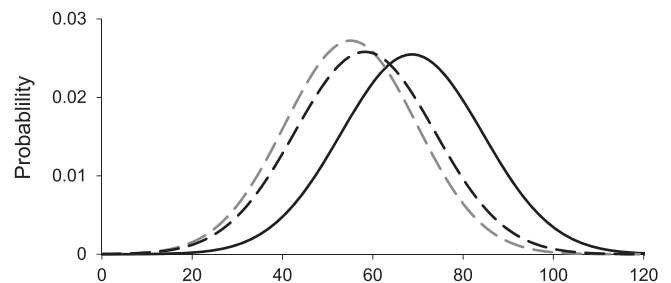
The source population, TM, was estimated to have 32 females in September 2014, with a 95% CRI of 28–41. With no harvesting this was projected to increase to 68 females in September 2016 (95% CRI = 42–103). Removal of 15 juvenile females was predicted to decrease this number to 55 (95% CRI = 31–88) if the translocation occurred in March 2015 and to 58 (95% CRI = 33–93) if the translocation occurred in March 2016 (Figure 1).

Average population projections for the destination population, BP, were positive under all three management alternatives (Figure 2). Both translocation alternatives slightly increased the projected mean number of females over 10 years, but the uncertainty around population size was quite large. The mean number of females in September 2024 was 80 if there no translocation, 82 or 83 if there was a translocation in 2015 or 2016, respectively, with 95% CRI = 0–100 for each alternative. Taking into account both parameter uncertainty and demographic stochasticity, the probability of

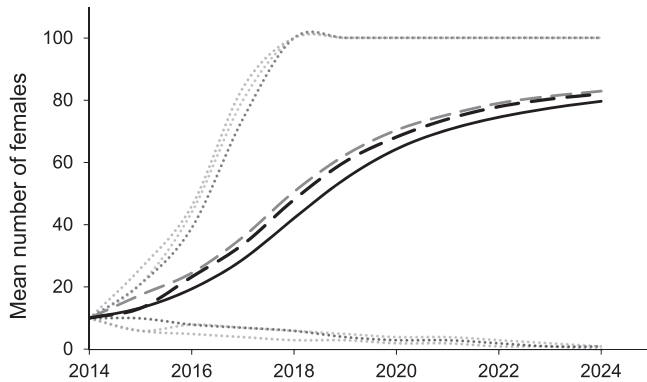
extinction within 10 years was <3% under all three alternatives.

### 3.2 | Evaluation of trade-offs

Obtained weights indicated that the most important objective for the HRG was “To maximize size of the BP population” - average normalized weight = 0.6 (ranged between 0.39 and



**FIGURE 1** Probability distributions for number of female hihi on Tiritiri Matangi Island (source population) in September 2016, under four alternatives: No harvest (solid black line), harvest of 15 females in March 2015 (dashed gray line) and harvest of 15 females in 2016 (dashed black line). Simulation starts in September 2014

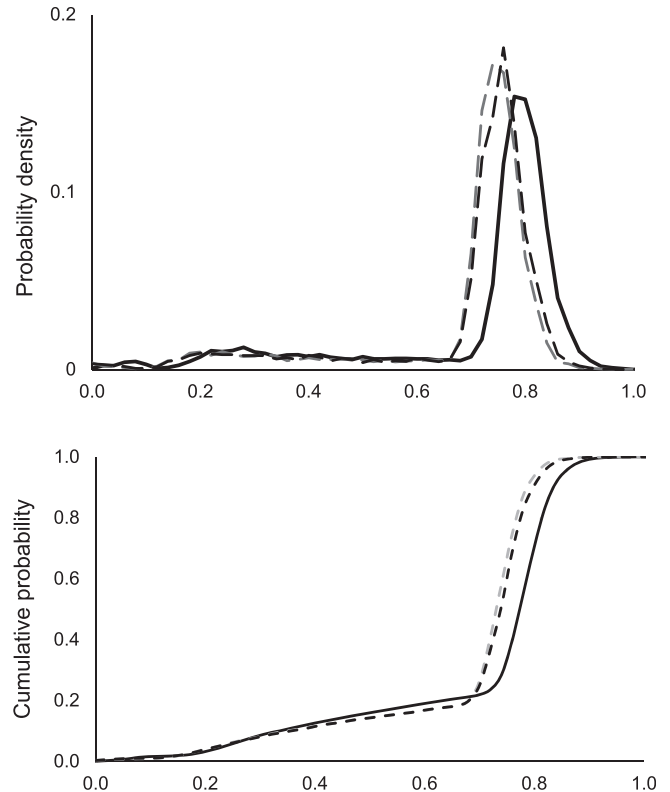


**FIGURE 2** Projections of hibi population growth in Bushy Park (destination population) over 10 years under three alternatives: No translocation (solid black line), translocation of 15 females in March 2015 (dashed gray line) and translocation of 15 females in March 2016 (dashed black line). Solid and dashed lines show mean numbers of female, and dotted lines show 95% credible intervals

0.74). “To maximize the size of the source population” was the second important objective, averaged normalized weight = 0.26 (ranged between 0.13 and 0.37). BP population persistence had the average weight of 0.13 (ranged between 0.09 and 0.26), and the least important objective was “cost”, with average normalized weight of 0.01 (ranged between 0 and 0.03). When average weights were used, the mean final score for alternative “no translocation” was slightly higher (0.75; CRI = 0.22–0.95) than that of the two translocation alternatives (translocation in 2015 – 0.72; CRI = 0.22–0.90; translocation in 2016 – 0.73; CRI = 0.22–0.91). Although the distributions of these scores overlapped greatly, the “no translocation” alternative was largely stochastically dominant (Figure 3). That is, it was clearly the best choice in about 80% of projections and the choice was ambiguous in the remaining projections. The relative difference between alternatives was insensitive to variation in stakeholder values, with these differences being consistently trivial in relation to the uncertainty in outcomes (Figure 4). Therefore, the group consensus based on these scores was to not conduct a further translocation.

## 4 | DISCUSSION

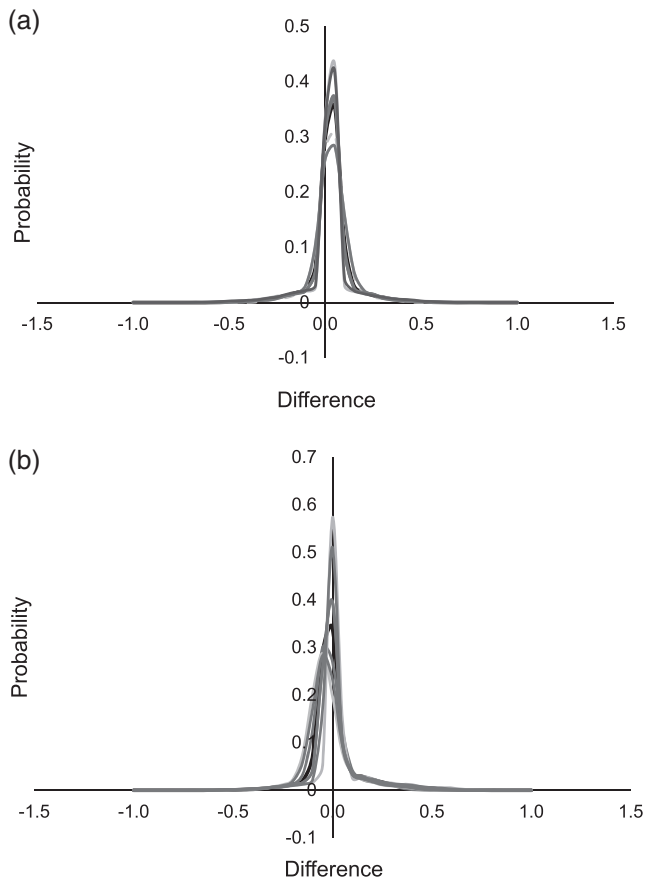
Although many threatened species require urgent actions, reintroduction decisions should not be made without careful consideration of how management alternatives perform in achieving clearly specified objectives. For many threatened species, the amount of available data may not be sufficient to calculate reliable vital rates, understand the ecosystem response to reintroduction, or track performance against other stated objectives, creating uncertainty in decisions. The key benefit of fully incorporating uncertainty is that the



**FIGURE 3** Probability distributions of the final score of three alternatives: No translocation (solid black line), translocation of 15 females in March 2015 (dashed gray line) and translocation of 15 females in March 2016 (dashed black line). Averaged objective weights were used

prediction intervals are likely to include the true parameter of interest whereas this may not be the case if uncertainty is ignored (Clark, 2003; Wade, 2002).

In our decision analysis, we combined three types of uncertainty: the uncertainty in parameter estimations, uncertainty in model selection, and demographic stochasticity. This made our projections more reliable but uncertain, representing the level of certainty that was appropriate with the data collected over 2 years after the initial reintroduction. As a result, uncertainty in the outcomes of management alternatives made choosing among them difficult, because the stakeholders had to consider the distributions of these outcomes. For instance, the No Translocation alternative had the highest final score among all, but the difference between the No Translocation and both Translocation alternatives appeared to be trivial when considering the overlapping distributions of the three final scores. Presenting the results in forms of probability distributions helped stakeholders to visualize the uncertainty associated with each alternative. The spread and the height of these distributions were similar, making it impossible to identify a less risky option. However, the cumulative distribution functions revealed that the “no translocation” alternative largely showed first order



**FIGURE 4** Eight probability distributions (corresponding to Hihi Recovery Group members) for the difference in final scores between alternatives: (a) “Translocation 2015” and “No translocation” and (b) “Translocation 2016” and “Translocation 2015”

stochastic dominance (i.e., under assumption that more is always better and where the curves do not cross then the lower curve represents the best alternative regardless of risk attitude) (Canessa et al., 2016). Given first order dominance there is no reason to further investigate the general risk tolerance of the group members (Canessa et al., 2016). However, risk tolerance could potentially have been explicitly accounted for by incorporating each group member's risk attitude into a simple utility function. A further step we could have taken would be to assess how reduction of uncertainty in particular parameters may have affected the decision. Such information could help decision makers understand the value of additional information and can help guide future research priorities.

Although we used averaged objective weights to obtain the final score distributions, we also re-ran the model using each of eight sets of objective weights to check the sensitivity of the results to individual values (Converse, Moore, & Armstrong, 2013). Despite HRG members assigning different weights to the objectives, the distributions of the final scores were very close (Figure 4), indicating that individual

weights did not influence the optimal choice. This provides valuable insight to the final decision maker by showing that the team share belief in the optimal management alternative despite perhaps having different objective priorities (e.g., representatives from both the source and destination sites may prioritize “their” site as more important). During our SDM process, three alternative actions were considered, including the status quo and two translocations 1 year apart. We were able to trade-off these alternatives against the stated management objectives whilst incorporating uncertainties in both population harvesting and reinforcement. Our timescales for projecting consequences were tailored to site-specific constraints. For assessing the impact on the source population, we used short (2 years) projections because that population is harvested regularly to provide birds for several reintroduction sites, and attempting to incorporate that into projections would involve unnecessary complexity. For our reinforcement, we set a 10-year projection to model initial population growth at the site without need to complicate projections with density regulation (it is unlikely the site would near carrying capacity in that time). Our results showed that proposed harvests would not threaten the source population, but also suggested they would have negligible effect on the size or persistence of the destination population. By explicitly comparing these alternatives the HRG could make a rational management decision. Overall, only a small portion of published reintroduction literature considers two or more alternative actions (Taylor et al., 2017) despite the obvious utility this approach has in ensuring the best management outcomes.

Many reintroductions around the world have failed because uncertainty and post-release monitoring were ignored and the decisions were made in isolation, without including a range of stakeholders, scientists, and the community in the decision-making process. For example, accounting for uncertainties in population projections could have warned decision makers that a reintroduced population of the endangered burrowing bettong (*Bettongia lesueur*) could potentially grow rapidly, causing negative effects on native plants and rodents in a closed ecosystem (Moseby, Lollback, & Lynch, 2018). Acknowledging the importance of post-release monitoring and using the data to inform reintroduction decisions could have prevented multiple reintroductions failures of the endangered oribi antelope (*Ourebia ourebi*) (Grey-Ross, Downs, & Kirkman, 2009) and European ground squirrel (*Spermophilus citellus*) (Mateju et al., 2010). SDM provides safe and transparent approach that guides decision makers through complex decision processes that often includes multiple objectives, various stakeholders and uncertain outcomes. In addition, explicit consideration of uncertainty allows decision makers to acknowledge the risk associated with each management

alternative. Finally, SDM has a potential to improve the overall success of reintroductions by encouraging decisions that are guided by clearly defined objectives and available knowledge to choose an optimal management action.

Using SDM, we developed a holistic approach that may improve reintroduction decisions. This approach, which involves modeling the source and the destination populations, and quantifying objective weights, may be adjusted to incorporate new available data, such as density dependency or genetic variation, and used for future management decisions of the BP hihi population or even modified to aid in reintroduction decisions of other threatened species.

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## CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

## AUTHORS CONTRIBUTIONS

All authors conceived of the initial idea for the manuscript and contributed to writing.

## DATA ACCESSIBILITY

All data is available in supplemental materials.

## ETHICS STATEMENT

This material has not been published in whole or in part elsewhere.

## ARTICLE IMPACT STATEMENT

We present a decision process for reintroductions that combines stakeholder values with population projections subject to uncertainty

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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