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Demographics of Reintroduction Special Section

Demographics of Reintroduced Populations: Estimation, Modeling, and Decision Analysis

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ABSTRACT Reintroduction can be necessary for recovering populations of threatened species. However, the success of reintroduction efforts has been poorer than many biologists and managers would hope. To increase the benefits gained from reintroduction, management decision making should be couched within formal decision-analytic frameworks. Decision analysis is a structured process for informing decision making that recognizes that all decisions have a set of components—objectives, alternative management actions, predictive models, and optimization methods—that can be decomposed, analyzed, and recomposed to facilitate optimal, transparent decisions. Because the outcome of interest in reintroduction efforts is typically population viability or related metrics, models used in decision analysis efforts for reintroductions will need to include population models. In this special section of the *Journal of Wildlife Management*, we highlight examples of the construction and use of models for informing management decisions in reintroduced populations. In this introductory contribution, we review concepts in decision analysis, population modeling for analysis of decisions in reintroduction settings, and future directions. Increased use of formal decision analysis, including adaptive management, has great potential to inform reintroduction efforts. Adopting these practices will require close collaboration among managers, decision analysts, population modelers, and field biologists.

KEY WORDS endangered species, management alternatives, objectives, population modeling, population viability analysis, structured decision making, translocation.

The global biodiversity crisis is now a well-documented phenomenon, with increasing numbers of species at risk of extinction due to direct or indirect anthropogenic causes (e.g., Lawton and May 1995, Pimm et al. 1995, Russell et al. 1998, Stuart et al. 2004). Management to reduce risk of species extinction includes a wide variety of actions, one of the more intensive of which is reintroduction. Reintroductions are intentional translocations of species into parts of their historically known range from which they have been extirpated (International Union for Conservation of Nature/Species Survival Commission [IUCN/SSC] 2012). Increasingly, the conservation biology literature also features discussion of conservation introductions—translocations of species outside of their historical range—primarily in the context of climate change adaptation (Hewitt et al. 2011, Chauvenet et al. 2012, IUCN/SSC 2012).

Source individuals for reintroductions may come from wild populations or from captive propagation programs. In either case, but especially in the latter case, reintroductions may be an expensive option for managers of endangered species. In addition to the monetary expense, reintroductions can have other costs, including negative effects on the source population, negative impacts on animal welfare, ecosystem-level risks, and public relations challenges for agencies undertaking reintroductions.

Despite this, reintroductions can be indispensable for species conservation. Without reintroduction, species can be confined to extremely limited ranges or to captivity. Limited population sizes and ranges can greatly increase the risk of species extinction. The risk of a catastrophic event seriously compromising the wild whooping crane (*Grus americana*) population across its restricted wintering range on the Gulf Coast of Texas is a major impetus for reintroductions of that species (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2005). A rat (*Rattus rattus*) invasion in the habitat of the sole remaining population of South Island saddlebacks (*Philesturnus carunculatus*) would have resulted in extinction of that species except for reintroduction elsewhere in response to the invasion (Merton 1975).

However, the success record of reintroductions has historically been quite poor (Lyles and May 1987, Griffith et al. 1989) resulting in the formation of the IUCN Reintroduction Specialist Group (IUCN 1987) and other efforts to improve reintroduction programs. Any set of tools aimed at increasing reintroduction success must include tools for demographic parameter estimation, population modeling, and integrated tools to understand how management

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actions may affect demography (Armstrong and Reynolds 2012). Because the primary fundamental objective of a reintroduction is typically to achieve a low probability of extinction in the population of interest (Burgman et al. 1993), demography is critical. Understanding habitat use, behavior, and other aspects of the life history of reintroduced populations will not be adequate if that understanding is not also linked to demography.

The focus of demographic analysis in a reintroduction setting must be on predictions of how management can influence demographic outcomes. That is, in the context of reintroduction management, the primary role of knowledge is to improve the decision-making capabilities of managers (Nichols and Williams 2006, Armstrong and Seddon 2008, Nichols and Armstrong 2012). Therefore, the focus of research and monitoring should be a better understanding of how management can improve the likelihood of favorable outcomes. In a similar vein, when discussing population viability analysis (PVA), Lindenmayer et al. (1993:752) concluded that PVA "is most effective when coupled with decision analysis and applied within an adaptive management framework."

With this in mind, we commenced a symposium entitled *Demographics of Reintroduced Populations: Estimation, Modeling, and Decision Analysis* at The Wildlife Society Annual Meeting in Waikoloa, Hawaii, in November 2011. Contributors to that symposium included many of the authors represented in this special section of the *Journal of Wildlife Management*. We were primarily interested in building on the ongoing conversation of how demographic analyses can facilitate better decision making for reintroduced populations. In this introductory contribution, we provide an overview of concepts for structuring reintroduction decisions that rely on demographic information.

REINTRODUCTION DECISIONS

What Are Reintroduction Decisions?

We will begin by describing what we mean by reintroduction decision making. In particular, what are reintroduction decisions? We are quite generally referring to any decisions about the whether, when, where, and how elements of virtually any reintroduction, throughout the various phases of the reintroduction process. Armstrong and Seddon (2008) identified 2 phases of a reintroduction: establishment and persistence. Alternately, Sarrazin (2007) identified release, growth, and regulation phases of reintroductions. Both classifications recognize that the dynamics of reintroduced populations change substantially over time. Consequently, the decisions faced by managers of these populations will change as well.

A critical consideration in decision making for reintroduced populations is uncertainty (Armstrong and Reynolds 2012). Reintroduction efforts are by their nature uncertain, because often few or no data exist about the habitat use, movements, and demography of the species in the reintroduction area. In addition, the ability of individuals—especially those sourced from captive populations—to acclimate to the reintroduction area is frequently uncertain. However, putting off acting until uncertainty is eliminated is not feasible, both because uncertainty can never be eliminated entirely and because the risk of extinction may increase if action is delayed while the species continues its decline.

A less frequently recognized challenge is that these decisions may have more than a single objective, in addition to the obvious objective of population establishment and persistence. In fact, many other considerations may weigh on managers' minds, including animal welfare, monetary constraints, impacts on source populations, and public relations (Parker 2008, Nichols and Armstrong 2012).

Decision Analysis for Reintroductions

If a primary goal of reintroduction biology is to improve the decision-making capacity of managers of reintroduction programs, we suggest that a useful conceptual frame is decision analysis, also frequently known as structured decision making (Fig. 1). Decision analysis is a process of deconstruction and analysis of decision components (Keeney 1992, Clemen 1996, Possingham et al. 2001, Gregory et al. 2012, Nichols and Armstrong 2012), where recognized components of decisions include the management objectives, the alternative management actions under consideration, a model that makes predictive links between the given alternatives and outcomes with respect to objectives, and some optimization scheme. The ultimate result of a decision-analytic process is identification of the optimal action: the best thing that a decision-maker can do amongst a set of alternatives for the best outcome that he or she can expect to achieve.

A key benefit of a formal decision-analytic process is that it encourages deliberative decision making focused on integrating all of the values of decision makers, all potential actions, and all pertinent scientific information to make the most informed decision possible. A decision-analytic process also enforces greater transparency in decision making because of the need to explicitly identify the process components. Consequently, the decision making process will be more readily understood and engaged with by stakeholders, more easily documented to facilitate similar decisions in the future, and more defensible to the public. Decision analysis stands opposed to a gut feeling approach to decision making and to approaches that fail to include critical objectives, consider an overly narrow set of alternatives, or ignore scientific information and uncertainty in the modeling step.

Building decision frameworks is as much a socio-political process as a scientific process (e.g., Lee 1999, Williams et al. 2007, Gregory and Long 2009). The process is designed to identify the optimal action given the objectives of the decision maker and stakeholders and given the set of potential alternatives as defined by this same group. Therefore, the process of building decision frameworks for reintroductions requires close collaboration and communication among managers, stakeholders, and the scientific experts represented by field biologists and modelers. For example, one increasingly popular model is collaborative

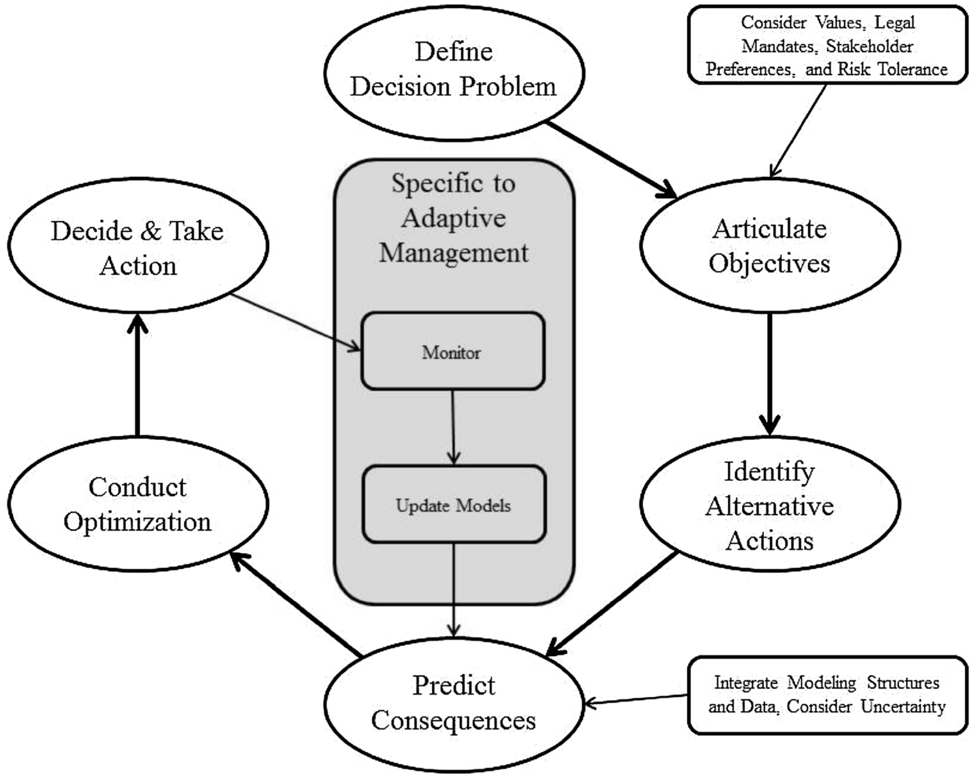

Figure 1. A simplified diagrammatic representation of the structured decision making process, adapted from Hammond et al. (1999), Runge and Cochrane (2009), Runge (2011), and Gregory et al. (2012). Major steps in structured decision making include defining the decision problem, articulating management objectives, identifying a feasible set of alternative actions, predicting consequences of alternative actions via models, and conducting optimization to identify the best possible action to take. A special case of structured decision-making, adaptive management, involves an iterative (e.g., annual) loop, which involves monitoring the outcome of decisions, updating models, and using updated models to inform decisions at the next time step.

development of frameworks via intensive workshops (e.g., Gregory and Long 2009, Blomquist et al. 2010, Converse et al. 2011). Development of a decision framework should proceed through decision problem definition, specification of objectives, and identification of alternative management actions largely under the direction of decision makers and stakeholders, facilitated by experts in decision analysis. Ideally, these components will be in place before ecological and other scientific considerations are brought in to inform development of models that provide the links between alternative actions and management objectives.

A major tenet of decision analysis is the formal consideration of uncertainty. Decisions must be made in the face of uncertainty, and the critical uncertainties that exist must be integrated explicitly into the analysis to seek out robust alternatives (Johnson et al. 2013). Alternatives that are robust to uncertainty are those that are predicted to lead to acceptably good outcomes regardless of how uncertainty resolves after the decision is implemented. Risk attitudes of decision makers must be taken into account in decision frameworks (Keeney 1992, Burgman et al. 1993, Harwood 2000, Burgman 2005). An individual's risk attitude is a measure of how that person responds to the risk of different possible outcomes from a decision made in the face of uncertainty, and this risk attitude should be represented directly in the objective function. The long-term adaptive management program for North American waterfowl harvest constitutes a well-known example, where the objective function integrates a utility function that devalues any harvest obtained when the population has declined below a minimum size (Nichols et al. 2007); this results in a strong tendency to select harvest strategies that guard against the risk of the population declining below this level. Finally, decision-analytic frameworks can also be extremely powerful for helping to identify key information gaps that either can be filled before a decision is made or can be filled over time and concurrently with ongoing management via an adaptive management process (Walters 1986).

Decision analysis also encompasses a set of tools for assessing the value of reducing uncertainty, known as value of information (Runge et al. 2011). The power of value of information analysis is the ability to translate expected information gains into the metric in which objectives are measured, for example, value of information would allow a manager to predict the expected increase in population size to be gained from a reduction in uncertainty (see examples in Moore and Conroy 2006, Moore and Runge 2012). The basic concept is that a reduction in uncertainty should result in greater confidence about which of a set of actions to take, thus reducing the risk of non-optimal outcomes. However, value of information can only be calculated when a clear decision context is identified, when measurable objectives are established, when alternatives are identified, and when a basic predictive model, perhaps based on expert knowledge (Runge et al. 2011), is established. In other words, the value of information cannot be assessed until a clear framework exists for how information will be used to improve decision making.

Engaging in a decision-analytic exercise before commencing design and data collection for research or monitoring programs can be a powerful method for ensuring that the final product is as useful to managers as possible (Nichols and Williams 2006). In a related sense, modeling exercises that are divorced from a clear decision context will not be as useful to managers. In decision analysis, the role of models is to provide a predictive link between alternatives and objectives; in particular, in making predictions of the form, "If we take action A, what outcome will we attain, in terms of our objectives?" Therefore, decision models will have, as inputs, parameters related to alternative management actions, and as outputs, measures of the objectives.

Use of a structured decision-analytic process for reintroduction planning can help to avoid pitfalls that can arise under unguided processes. One of the very first tasks in a structured process is to identify the decision maker with authority over the decision itself, as well as stakeholders with a vested interest in the process. If this step is overlooked under a less formalized approach, the outcome may have insufficient ownership and buy-in among stakeholders and perhaps little consequence to the decision maker. Because a structured process is designed to elicit the perspectives of the decision maker and stakeholders, the outcome will likely have relevance to their needs, capabilities, and constraints; that is, a structured process can avoid an unsatisfactory outcome that emerges from asking the wrong questions. Furthermore, a wider breadth of important management objectives and viable alternative actions is likely to be identified under a structured process (Keeney 1992). Finally, the process is designed to reduce semantic uncertainty (Regan et al. 2002) by enforcing clear and operational definitions of objectives. For example, the process will require an important discussion about what constitutes a successful reintroduction—whether a particular population size, a particular probability of persistence, or otherwise. A process that lacks that discussion may yield objectives that are not truly shared amongst key participants and are not operationally defined.

Some reintroduction decision settings may lend themselves to an adaptive management approach (Runge 2011, McCarthy et al. 2012). Adaptive management is a specific form of decision analysis designed to resolve uncertainty as decisions are being made, ultimately leading to better decision making in the future (Walters 1986, Williams et al. 2007). Under adaptive management, 2 conditions hold: a setting in which a recurring decision is made through time and the existence of epistemic uncertainty (uncertainty arising from limited knowledge of a system) that has relevance to the choice of a best decision. Under this approach, uncertainty is represented as a discrete probability distribution over a set of models, or as a continuous joint distribution on a set of parameters within a single model. In either case, the predicted outcome for a given management action is described only in probabilistic terms, with the precision of these probabilities corresponding to degree of uncertainty about modeled mechanisms. When uncertainty is high, as it often is at the outset of any conservation program, decision quality (the ability to provide a reliable return on management objectives) may be quite poor. However, through the collection of monitoring data and the confrontation of model predictions with these data, uncertainty is gradually and continuously reduced. That is, the process of decision making itself is used to improve the quality of future decision making. Illustrative examples for threatened species include Johnson et al. (2011), Moore et al. (2011), and Tyre et al. (2011).

Adaptive management can operate without any formal optimization of management action; even if management actions are selected without optimal guidance, these actions can nevertheless be informative about underlying system processes. However, the employment of an optimization framework is the ideal approach because it formally recognizes the tradeoffs amongst management objectives that decision makers and stakeholders care about; for example, identifying the management actions that will most likely lead to population persistence, given a fixed budget. Often the approach will involve use of an optimization technique such as dynamic programming. Here, the dynamics of the system and its future conditions are formally recognized and accounted for in the optimization, so that decision policies that result from the analysis can truly be characterized as sustainable; that is, the selection of today's action is based on an accounting of future resource returns. Furthermore, optimal dynamic policies may be derived in 2 ways that differ in whether projections of future system knowledge are or are not recognized (McCarthy et al. 2012). In a passive adaptive policy, the optimization takes into account how the resource state (e.g., the reintroduced animal population) is expected to change through time in response to management actions, but not how knowledge might also change. In an active adaptive policy, the expected change in knowledge is also accounted for, and so certain actions may be optimal at certain time points at least partly because they facilitate learning.

Demographic Decision Models for Informing Reintroduction Efforts—A Review

Relatively rich literature already exists on the application of demographic decision models to reintroduction decision making, and we briefly review this literature here. We define demographic decision models as models of demography that are used to explicitly predict population-level outcomes (e.g., probability of persistence, population size, population growth rate, and similar metrics) under alternative actions. When applied to reintroductions, alternative management actions will include things such as different release sites, different numbers released, different release methods, and different types or intensities of release site management.

The largest set of examples of demographic decision models for reintroductions include those that focus primarily on detailed demographic information (e.g., age- and sex-specific demographic rates), and use simulation to evaluate management actions in terms of extinction probability, population size, or related metrics; in other words, PVA (Boyce 1992). PVA as applied to reintroduction management began to appear in the literature in the early- to mid-1990s, coincident with increased awareness and use of PVA in general (e.g., Menges 1990, Boyce 1992, Lindenmayer and Possingham 1996, Beissinger and Westphal 1998) that built upon earlier seminal work (e.g., Shaffer 1981, Crouse et al. 1987, Lande 1988).

A number of population viability models have been applied to the evaluation of decision alternatives for reintroduced (and source) populations. Because a majority of this literature appears in an extensive review undertaken by Armstrong and Reynolds (2012) we have condensed our review (Table 1), and here only highlight the types of decisions that have been addressed with population viability models applied to reintroduced populations. Decision types we identified include those associated with the initial release action: the numbers to release, the age classes to release, the sex ratio of released animals, the temporal pattern of releases, the spatial pattern of releases, and the release method. An additional set of decision types include those that occur after a population is established: the numbers for supplemental releases, the age classes for supplemental releases, the temporal pattern of supplemental releases, the spatial pattern of supplemental releases, harvest or control of the reintroduced population, and post-release habitat management.

At the commencement of a reintroduction program—during the establishment phase (Armstrong and Seddon 2008) or the release phase (Sarrazin 2007)—managers will often be particularly concerned with the numbers and types of animals to initially release. The majority of the literature of this type includes an evaluation of initial numbers: how many individuals should be released to achieve an acceptable probability of success (e.g., achieving an explicitly stated probability of long-term persistence) and how many individuals can be sustainably removed from source populations? In addition to the numbers released, models have also frequently been built to consider the temporal pattern of release, including the number of years and the intervals at which releases should be conducted to maximize the probability of success. This aspect of reintroduction planning is often closely tied to the number released, as releasing individuals for more years will generally yield a greater total number released. Also, the demographic membership of the individuals released is sometimes considered. This may include the sex ratio or age structure.

The spatial configuration of initial releases is another frequent consideration (i.e., where to site releases). At 1 level, this can involve the decision of whether to undertake releases at a particular release site as a function of the predicted demographic response to site-specific conditions. At another level, spatial considerations include whether to establish 1 or multiple independent populations, which can be dealt with implicitly based on the relative risk of a single large versus several small populations, or explicitly by including elements such as the probability of interactions between multiple populations as a function of distance and the availability of movement corridors.

After the completion of the initial releases, 3 classes of management actions are available to managers. First is supplementary releases—whether and how to supplement the population with additional individuals (how many individuals, for how many years, with what demographic structure, and with what genetic characteristics, etc.) to increase viability. A number of examples are focused on supplementary releases. We note that a perceived gray area may exist between what constitutes an initial release effort and what constitutes supplementary releases. To clarify this, we suggest that initial releases may simply be defined as the initial number of individuals committed to the release program by decision makers. A variation on the concept of supplementary releases is movement of individuals among multiple subpopulations established during the reintroduction, primarily designed to increase population persistence by reducing inbreeding. Second is the question of habitat management, including vegetation management, predator control, and the like. Demographic models designed to consider post-release habitat management could potentially constitute a broad category; interestingly, relatively few examples exist. Finally, in a small set of situations, reintroduction efforts have achieved a level of success wherein control of the reintroduced population, or harvest of the reintroduced population for direct human benefit, has been contemplated.

In addition to the types of analyses described above and related examples (Table 1), a much smaller set of papers employ classical decision-analytic concepts and tools for identifying optimal policies for single or multiple objectives. We highlight examples here in greater detail because they illustrate tools that we expect are less familiar to biologists involved with reintroduction efforts.

Most of the explicitly decision-analytic efforts have used optimization methods designed for single time point decisions rather than dynamic and/or adaptive decisions. Decision trees are a classical tool in decision analysis, and they have been applied to several reintroduction decisions. Decision trees are designed to optimize decisions in the face of discrete uncertainties, using expected values or utilities. Characteristic of these efforts is demographic information that is quite simple and often is developed using expert opinion rather than data. However, these examples illustrate the value of explicit structuring of decision problems (i.e., identification of quantitative objectives and discrete alternatives) and a method for handling uncertainty. Examples include Maguire (1986), who applied a decision tree, with minimizing expected probability of extinction as the objective, to a theoretical decision about whether to establish a second population of an endangered species (nominally, though not specifically, a population of whooping cranes) using reintroduction. Maguire et al. (1988) used a decision tree to examine whether to aggressively protect habitat in

Table 1. An overview of population simulation modeling papers applied to simulating management actions for reintroduced populations. Information provided includes the species of interest and the type of management actions modeled. Action types include (A) numbers to release (in some cases this involved prediction of effects on a source population in addition to or instead of effects on a reintroduced population), (B) age classes to release, (C) sex ratio of released animals, (D) temporal pattern of releases, (E) spatial pattern of releases, (F) numbers for supplemental releases, (G) age classes for supplemental releases, (H) temporal pattern of supplemental releases, (I) spatial pattern of supplemental releases, (J) harvest or control of the reintroduced population, and (K) post-release habitat management.

		Management action type										
Citation	**Species**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Akçakaya et al. (1995)	Helmeted honeyeater (*Lichenostomus melanops*)	•										
Armstrong and Ewen (2001)	New Zealand robin (*Petroica australis*)						•					
Armstrong et al. (2002)	Hihi (*Notiomystis cincta*)											•
Armstrong and Davidson (2006)	North Island saddleback (*Philesturnus rufusater*)	•										•
Armstrong et al. (2006*a*)	North Island robin (*Petroica longipes*)											•
Armstrong et al. (2007)	Hihi											•
Bach et al. (2010)	Wild dog (*Lycaon pictus*)	•					•		•			
Bar-David et al. (2008)	Persian fallow deer (*Dama dama mesopotamica*)											•
Bell et al. (2003)	Pitcher's thistle (*Cirsium pitcheri*)	•	•									
Bustamante (1996)	Bearded vulture (*Gypaetus barbatus*)						•					
Burgman et al. (1994)	Leadbeater's possum (*Gymnobelideus leadbeateri)*	•	•									
de Jong et al. (1996)	Eurasian lynx (*Lynx lynx*)	•			•		•		•			
Dimond and Armstrong (2007)	North Island robin	•										
Dixon et al. (1991)	Scimitar-horned oryx (*Oryx dammah*), Addax (*Addax nasomaculatus*)	•		•	•							
Eastridge and Clark (2001)	Black bear (*Ursus americanus*)						•		•			
Fernández et al. (2006)	Wild boar (*Sus scrofa*)					•						
Green et al. (1996)	White-tailed eagle (*Haliaeetus albicilla*)						•		•			
Gusset et al. (2009)	Wild dog	•			•		•					
Haig et al. (1993)	Red-cockaded woodpecker (*Picoides borealis*)						•		•			
Howells and Edwards-Jones (1997)	Wild boar	•					•					
King et al. (2013)	Western lowland gorilla (*Gorilla gorilla gorilla*)						•		•			
Kirchner et al. (2006)	*Centaurea corymbosa*	•				•						
Kramer-Schadt et al. (2006)	Eurasian lynx (*Lynx lynx*)	•				•						
Leaper et al. (1999)	Wild boar	•				•						
Mackey et al. (2009)	African elephant (*Loxodonta africana*)										•	
Martínez-Abraín et al. (2011)	Crested coot (*Fulica cristata*)	•	•		•							
McCallum (1994)	Bridled nailtail wallaby (*Onychogalea fraenata*)	•										
McCallum et al. (1995)	Bridled nailtail wallaby	•				•						
McCarthy (1994)	Helmeted honeyeater	•	•		•							
Moore et al. (2012)	Whooping crane (*Grus americana*)						•		•			
Münzbergová et al. (2005)	*Succisa pratensis*	•				•						
Muths and Dreitz (2008)	Wyoming toad (*Bufo baxteri*)	•										
Nolet and Baveco (1996)	Eurasian beaver (*Castor fiber*)						•					
Novellie et al. (1996)	Cape mountain zebra (*Equus zebra zebra*)	•										
Parlato and Armstrong (2012)	North Island robin					•						
Pedrono et al. (2004)	Ploughshare tortoise (*Geochelone yniphora*)	•	•									
Perkins et al. (2008)	Grasshopper sparrow (*Ammodramus savannarum*)	•				•						
Robert et al. (2004)	Griffon vulture (*Gyps fulvus*)		•									
Saltz (1996)	Persian fallow deer	•	•									
Saltz (1998)	Persian fallow deer, Arabian oryx (*Oryx leucoryx*)	•										
Sarrazin and Legendre (2000)	Griffon vulture	•	•		•							
Schaub et al. (2009)	Bearded vulture (*Gypaetus barbatus*)						•		•			
Slotta-Bachmayr et al. (2004)	Przewalksi's horse (*Equus caballus przewalskii*)						•	•	•			
Somers (1997)	Warthog (*Phacochoerus aethiopicus*)						•		•		•	
South et al. (2000)	Eurasian beaver	•				•						
South et al. (2001)	Eurasian beaver					•						
Southgate and Possingham (1995)	Greater bilby (*Macrotis lagotis*)	•				•						
Steury and Murray (2004)	Lynx (*Lynx canadensis*)	•				•						
Tocher et al. (2006)	Hamilton's frog (*Leiopelma hamiltoni*)	•	•									
Todd et al. (2004)	Trout cod (*Maccullochella macquariensis*)	•	•									
Varley and Boyce (2006)	Wolf (*Canis lupus*)										•	
Wakamiya and Roy (2009)	Peregrine falcon (*Falco peregrinus anatum*)						•		•	•		
Wood et al. (2007)	Tree squirrels (*Sciurus spp.*, *Tamiasciurus hudsonicus*)	•										

anticipation of a black-footed ferret (*Mustela nigripes*) reintroduction effort, again using probability of extinction as the objective. Finally, Soulé (1989) used a decision tree to predict probability of extinction in 25 years for the concho water snake (*Nerodia harteri paucimaculata*); the analysis integrated expert assessments of the likelihood of successful breeding under different management actions, and the associated probability of extinction for each action-breeding combination. One management action considered was reintroduction of the snake into unoccupied river reaches.

Additional examples of decision analysis applied to solve single time point reintroduction decisions illustrate a wide variety of decision-analytic tools. Hearne and Swart (1991) developed a series of differential equations representing an age-structured black rhino (*Diceros bicornis*) population and used these equations to identify optimal policies regarding maximum sustainable take from a source population, maximizing growth of a reintroduced population, and a policy for maximizing overall growth of the species (both source and reintroduced populations simultaneously). Linear programming was used in a spatial optimization problem to determine the optimal spatial arrangement of prairie dog (*Cynomys* spp.) control activities—given constraints on the overall amount of control that would occur—to maximize numbers in a reintroduced population of black-footed ferrets, while taking into account local population growth and dispersal (Bevers et al. 1997). Haight et al. (2000) used robust optimization to analyze several reintroduction decisions, including choice of release method, the relative allocation of budget to monitoring versus release, and how to allocate budget to translocation infrastructure when future funding is uncertain. The authors considered balancing 2 objectives: maximizing population size post-release and minimizing the degree to which the population fell below some threshold (i.e., minimizing risk of a poor outcome) and demographic data included variable population growth rates for a hypothetical species.

Another set of explicitly decision-analytic efforts are those that have focused on dynamic, stochastic, and potentially adaptive decision settings. Lubow (1996) demonstrated the utility of stochastic dynamic programming for identifying state-dependent optimal actions (i.e., the best decision alternative for each of the possible future states of a population) around translocating animals between 2 reserves to maximize persistence probability. The demographic information employed was stochastic intrinsic population growth rate under an assumption of density dependence. Similarly, Possingham (1996) demonstrated solution of a Markov decision process via a spatially implicit metapopulation model with patch colonization and extinction probabilities, along with stochastic dynamic programming, to solve a decision problem regarding reintroduction of a population in an available habitat patch versus creation of a new habitat patch. Reintroduction of trout cod (*Maccullochella macquariensis*) in southeastern Australia was the focus of a unique effort to identify not just optimum reintroduction strategies (variable intensities of releases for variable numbers of years) but to simulate the entire adaptive management cycle and explore concepts such as risk attitude and its impact on optimal strategy selection, and the value of monitoring in informing management (Bearlin et al. 2002). These authors used a detailed age-structured stochastic population model integrating environmental and demographic stochasticity, as well as structural uncertainty about population function. Finally, Tenhumberg et al. (2004) used stochastic dynamic programming to identify optimal state-dependent actions, given the problem of moving individuals between captive and wild populations to maximize the probability of long-term persistence in the wild. The demographic data used were constant birth and survival probabilities applied to a female single-age population with demographic stochasticity; the approach was demonstrated based on demographic data for Arabian oryx (*Oryx leucoryx*).

The development of demographic decision models should depend on the needs of decision makers. Too often, science that is intended to be used in decision making is conducted without explicit recognition of the particular decisions that managers are facing. A greater integration of science and management is needed, and reintroduction practice will be best served if high quality scientific information is embedded into well-conceived decision frameworks. This will require collaborative efforts among managers, biologists, and decision analysts.

Demographic Models for Reintroduced Populations—Special Issues

The process of building demographic models for reintroduced populations is not fundamentally different from that used for any population subject to management decisions. The most fundamental aspects are to estimate survival and fecundity rates, and dispersal if likely to be relevant. This is typically done using data collected after reintroduction, but can also be done before a reintroduction using, for example, data from other sites (Parlato and Armstrong 2012). These models can then be used to make population projections that allow for uncertainty in parameter estimation and model choice as well as environmental stochasticity (Armstrong and Reynolds 2012). However, some key features of reintroduced populations typically affect the types of models used.

First, the initial population is usually quite small in relation to the expected carrying capacity. Therefore, ignoring negative density dependence in initial models and focusing on the key issue of whether the population will grow or decline is often reasonable. Small population sizes also mean that accounting for demographic stochasticity in projections is essential, and may mean that Allee effects (positive density dependence) need to be included. Second, the sex and age structure of the initial population is determined by the individuals released and may be quite different from the stable distribution. Therefore, analysts must estimate age- or stage-specific demographic rates, and use these to infer the finite rate of increase (i.e., the growth rate expected when the population stabilizes). The projections can also be used to decide the optimal composition of the release group. Third, reintroduced populations are initially subject to post-release effects due to the stresses associated with translocation (Armstrong and Reynolds 2012). Therefore, one must discount the elevated mortality and/or dispersal that often occur immediately after release when making long-term projections; considering longer-term effects may also be important. Explicitly modeling the post-release effects is useful for guiding decisions about optimal numbers released and release methods.

Future Developments in Reintroduction Decision Models

In the future, we hope to see conservation biologists building decision models for guiding reintroductions that continue to push the methodological boundaries (see also Armstrong and

Reynolds 2012). First, continued development and application of advanced demographic estimation methods will improve the process of parameterizing decision models. For example, the use of Bayesian hierarchical models in demographic estimation (Royle and Dorazio 2008) facilitates the inclusion of both environmental variation and parametric uncertainty (e.g., Moore et al. 2012, Parlato and Armstrong 2012). In addition, ongoing developments in integrated population modeling (Besbeas et al. 2002, 2003, Brooks et al. 2004; Thomas et al. 2005; Abadi et al. 2010) hold promise for improved demographic estimation from small reintroduced populations by combining multiple data streams in the estimation process.

Conservationists also need a greater integration of genetic and demographic information in reintroduction decision models to deal explicitly with the demographic effects of inbreeding (Kirchner et al. 2006, Robert et al. 2007), which have been considered frequently in planning reintroductions (e.g., via VORTEX; Lacy 1993; any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government) although generally from a theoretical rather than empirical basis. Jamieson and Lacy (2012) provide a useful review. Integration of genetic information to account for not just inbreeding considerations, but individual quality as well, may also be an avenue for guiding reintroduction decisions (Robert et al. 2003, Converse et al. 2012).

Finally, increasing use of explicitly decision-analytic concepts should lead to better integration of management and science, and better fostering of conversations between managers and scientists, to result in decision models that are of maximal utility to managers. Application of decision-analytic concepts should also lead to increased recognition and one hopes, adoption, of adaptive management principles in reintroduction management (Armstrong et al. 2007, McCarthy et al. 2012) wherein information in a reintroduction program is formally accumulated over time. When building models relevant to decision making, formal use of data from other reintroduced programs will increase the speed with which reasonably precise information becomes available for decision-making (Holland et al. 2009, McCarthy et al. 2012, Parlato and Armstrong 2012).

OVERVIEW OF CONTRIBUTIONS IN THIS SPECIAL SECTION

We recognize 3 different classes of quantitative methods involved in the construction of demographic decision models: estimation, population modeling, and decision analysis. Each of the papers in this special section highlights 1 or more of these classes. To build demographic decision models, ideally one would begin with structuring the decision itself, before any estimation or modeling were done, or even before data were collected. However, in practice, often the first step taken is to use data available from post-release monitoring to estimate demographic rates (survival, reproduction, and migration). For these demographic parameters to be useful in building demographic decision models, they must conform to the needs of the decision problem. For example, if managers want to consider predator removal actions because they hypothesize that those actions will increase reproductive success, then reproduction would ideally be modeled as a function of predator control (sensu Armstrong et al. 2006*b*). If data to build such a model are not available, one may use expert elicitation to predict expected effects of predator control on reproductive rates.

Once demographic parameters and relationships are estimated, the estimates can be used to develop population models. This process involves integrating demographic rates to make projections about population outcomes (e.g., population sizes, extinction probabilities, or growth rates). Again, the structure of the model must anticipate how it will be used in a decision-making process. In particular, modelers should work directly with managers to identify the best metrics for their management objectives. For example, should the model predict population size, population growth rate, or probability of extinction some number of years after termination of releases (where number of years may depend on the particularities of the case, including the manager's risk tolerance, the management time horizon, or the life history of the species in question)?

Finally, the models will be used to test different alternative actions. This is the step that requires the greatest integration of the skills of biologists, modelers, and managers. The alternative actions modeled should truly capture those under consideration by the managers. During discussions, managers should be clear if decisions are 1-time decisions (e.g., should we undertake a release effort at site *X*) or recurrent, and potentially adaptive, decisions (should we release animals in year t, in year $t + 1$, etc.). To provide the most useful information to managers, models must reflect the decisions faced by managers. In fact, the conversation should proceed in both directions; modelers who develop greater familiarity with decision-analytic tools and applications will be able to offer managers alternative ways of thinking about, and solving, their decision problems.

Reynolds et al. (2013) focus primarily on the estimation and modeling steps. These authors detail the comparative demography of an established population and a newly released population of Laysan ducks (*Anas laysanensis*) in the Northwestern Hawaiian Islands. Monitoring allowed for the detection of substantial differences in reproduction between these populations. The reintroduced population, released into unoccupied habitat with a relatively large carrying capacity compared to the established population, demonstrated the potential to grow quickly, with an estimated finite rate of increase >3 in the initial years. This result has clear implications for planning future reintroduction efforts for this species, as rapid growth implies that fewer founders may be needed to establish a target population size. However, another aspect of demography is genetic variability of the population. Genetic variability, as the raw material for natural selection and for avoiding inbreeding depression, has a long-term effect on demography. The authors therefore also estimate the number of releases required to maintain rare alleles in isolated Laysan duck populations.

Bell et al. (2013) carry out a validation study to emphasize how decision making about reintroductions can be sensitive to choices made in the construction of predictive models. They analyze 8 years of demographic information from a multi-site restoration project of the threatened dune thistle (*Cirsium pitcheri*) to parameterize projection models, and construct models under alternative mechanisms for incorporating environmental stochasticity and correlation among vital rates. They use each model to project population attributes over a subsequent 5-year period of population monitoring, and show that prediction accuracy and precision for each of the attributes were sensitive to model choice, and that no single model is uniformly superior for all attributes. They demonstrate the value of demographic models for making short-term projections but also emphasize that whenever viability models are used to support reintroduction decision making, practitioners should proceed with care and not rely exclusively on the inference from a single model.

Gedir et al. (2013) consider how prior information can be used to improve population projections in the initial years after reintroduction, potentially reducing monitoring requirements. They make population projections for reintroduction of a New Zealand forest bird, the North Island saddleback (*Philesturnus rufusater*) to a predator-fenced reserve, using 1, 2, or 3 years of post-release data with or without prior information. The prior information was gleaned from 2 previous reintroductions of the same species at other sites. They use a modeling approach whereby parameter estimation and population projections are done simultaneously, allowing estimation of uncertainty to be fully propagated into the projections. They consider the question of how much post-release data are needed to be confident that a reintroduction is successful, and suggest that monitoring, in their case, could have been discontinued about 1 year earlier if the prior information had been used.

Collazo et al. (2013) evaluate optimal release strategies for Puerto Rican parrots (*Amazona vittata*) in 3 populations: an established but poorly performing population, a newly reintroduced and potentially increasing population, and a prospective new reintroduction. The authors formulate the problem as a Markov decision process, and solve for optimal state-dependent decisions wherein available individuals can be allocated across the 3 populations each year. To account for epistemic uncertainty, the authors develop 4 different scenarios that include different reproductive and survival rates for the 3 populations, and show how optimal decisions depend on the specific demographic rates. Finally, the authors also use these 4 models to motivate the idea of developing an adaptive management program for Puerto Rican parrot releases, wherein decisions would be based on the full set of models and the relative belief in those models, allowing management to adapt as knowledge accumulates through time.

Runge (2013) extends the idea of adaptive management in a setting in which the optimal decision about releases takes into account the expected value of information offered by the decision for reducing uncertainty. In the case of reintroduction of griffon vultures (*Gyps fulvus*), the decision about the relative numbers of juvenile and adult birds to release each year is unclear because of uncertainty about the short-term survival probability of released adults. Runge (2013) expresses the current uncertainty about this vital rate as a dynamic information state (i.e., the parameters of a probability distribution for the rate), and uses a dynamic programming approach to compute a decision policy prescribing the proportion of adult birds to release with respect to time and current knowledge about survival. Through monitoring, uncertainty about short-term survival of adults is progressively reduced and reflected in future decision making. He demonstrates that the nature of the optimal decision changes according to the degree of uncertainty in the parameter and the amount of time left in the release program; where one could potentially uncover information that could improve the quality of future decision making, the policy will offer decisions that probe for this learning. Thus, this is an example of active adaptive management (Walters 1986), where the pursuit of information is explicitly considered to the degree that it aids decision making.

Converse et al. (2013) focus on 2 challenges in reintroduction decision making—uncertainty represented by competing models of demographic processes, and multiple objective tradeoffs. They make the argument that modeling for population objectives alone will often not be sufficient for the needs of decision makers who are wrestling with the challenge of considering tradeoffs among multiple ecological and social values in the context of a reintroduction effort. They illustrate a decision-analytic process that deals with these tradeoffs explicitly to inform a decision about whether and how to undertake supplementary releases to a reintroduced population of whooping cranes. They also illustrate methods for grappling with a major source of uncertainty in reintroduction programs, especially for species like whooping cranes with delayed reproduction, the question of whether second- and later-generation birds will perform demographically in a substantially different way than first-generation released individuals.

SUMMARY

Population models are critical for the management of reintroduction efforts, as a primary objective of these efforts is to attain viable populations. In a decision-making setting, population models are critical for predicting the impacts of different management actions on population metrics of interest, such as probability of persistence, population size, and population growth rate. Formalized decision-making settings have the potential to lend increased robustness and transparency to reintroduction decisions—surely a worthwhile goal given the great expense of these efforts, the risks, and the relatively poor record of success to date. A relatively rich and expanding literature in formal decision analysis, frequently known as structured decision making, provides a valuable resource to biologists, managers, and modelers working on reintroduction efforts. Increasing the use of formal decision analysis for iterative reintroduction decisions beset by uncertainty—in other words, adaptive management—is the next hill to conquer.

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