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Demographics of Reintroduction Special Section

A Matter of Tradeoffs: Reintroduction as a Multiple Objective Decision

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ABSTRACT Decision making in guidance of reintroduction efforts is made challenging by the substantial scientific uncertainty typically involved. However, a less recognized challenge is that the management objectives are often numerous and complex. Decision makers managing reintroduction efforts are often concerned with more than just how to maximize the probability of reintroduction success from a population perspective. Decision makers are also weighing other concerns such as budget limitations, public support and/or opposition, impacts on the ecosystem, and the need to consider not just a single reintroduction effort, but conservation of the entire species. Multiple objective decision analysis is a powerful tool for formal analysis of such complex decisions. We demonstrate the use of multiple objective decision analysis in the case of the Florida non-migratory whooping crane reintroduction effort. In this case, the State of Florida was considering whether to resume releases of captive-reared crane chicks into the non-migratory whooping crane population in that state. Management objectives under consideration included maximizing the probability of successful population establishment, minimizing costs, maximizing public relations benefits, maximizing the number of birds available for alternative reintroduction efforts, and maximizing learning about the demographic patterns of reintroduced whooping cranes. The State of Florida engaged in a collaborative process with their management partners, first, to evaluate and characterize important uncertainties about system behavior, and next, to formally evaluate the tradeoffs between objectives using the Simple Multi-Attribute Rating Technique (SMART). The recommendation resulting from this process, to continue releases of cranes at a moderate intensity, was adopted by the State of Florida in late 2008. Although continued releases did not receive support from the International Whooping Crane Recovery Team, this approach does provide a template for the formal, transparent consideration of multiple, potentially competing, objectives in reintroduction decision making.

KEY WORDS Allee effect, expert elicitation, Florida, *Grus americana*, model weights, population modeling, structured decision making, whooping cranes.

Decisions can be made challenging and complex by multiple factors (Clemen 1996). Two factors familiar to managers of endangered species are substantial scientific uncertainty and the presence of complex and potentially competing objectives held by managers and stakeholders. A specific subset of endangered species management decisions are reintroduction decisions including whether, where, when, and how to translocate and establish an endangered species in a part of its historical range that is currently unoccupied (International Union for Conservation of Nature 1987). Reintroductions are a notoriously difficult class of management actions with relatively low success rates (e.g., Griffith et al. 1989, Wolf et al. 1996, Fischer and Lindenmayer 2000).

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Armstrong and Seddon (2008) provided a description of the key uncertainties that are relevant to reintroduction decisions. These uncertainties, if unaddressed, are expected to make reintroductions less successful, including uncertainties at the ecosystem, metapopulation, and population levels. At the population level, these authors recognized uncertainties arising from variation in outcome due to release method, pre- and post-release management, habitat conditions, and genetics. In fact, almost by definition, serious scientific uncertainty is an issue in reintroduction efforts because the species is being reintroduced into an environment that it does not currently occupy so the ability to understand fundamental aspects of the ecology and management of a reintroduced species is limited.

Less recognized is that reintroduction decisions are frequently made more challenging by the presence of multiple and potentially competing objectives, such as establishing a new population, maintaining genetic diversity in captive-breeding centers, minimizing costs, providing recreational opportunities, or preventing a negative impact to the ecosystem. Competing objectives make it necessary for decision makers to grapple with tradeoffs, such as tradeoffs between minimizing costs and increasing the probability of a successful reintroduction. As an example, one may consider management of the endangered whooping crane (*Grus americana*). A goal of the Whooping Crane Recovery Plan (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2005) is the establishment of 1–2 additional populations of whooping cranes in North America. This goal was pursued through the release of captive-reared chicks beginning in 1993 to establish the Florida Non-migratory Population (Nesbitt et al. 1997, 2001). However, releases were suspended in 2004 because of concerns about the demographic performance of the reintroduced flock (Folk et al. 2008). In the subsequent years, the International Whooping Crane Recovery Team (IWCRT) directed captive-reared production to a second reintroduction program. This program, beginning with releases in 2001, was aimed at establishing a migratory population summering in Wisconsin and wintering in Florida: the Eastern Migratory Population (Urbanek et al. 2005).

However, managers at the Florida Fish and Wildlife Conservation Commission (FWC) remained interested in considering additional releases to the Florida Non-migratory Population pending a thorough analysis of the outlook for successful establishment of the flock. Specifically, FWC needed to decide whether to request from the IWCRT that some portion of captive-reared production again be directed to the Florida Non-migratory Population. In 2008, FWC requested that collaborators at the United States Geological Survey Patuxent Wildlife Research Center (PWRC) develop a structured decision making framework to support this decision-making process (Moore et al. 2008). The framework was built largely around a population model that captured uncertainty about the probability of successful establishment. However, the framework also needed to recognize the multi-objective nature of the decision that FWC faced, where managers were concerned about not just the probability of successful establishment of the Florida Non-migratory Population but also factors such as costs and the potential impacts on the reintroduction of the Eastern Migratory Population.

Structured decision making is a decision-analytic process that emphasizes deconstruction, analysis, and synthesis of the components of a decision to identify an optimal course of action (Clemen 1996, Nichols and Armstrong 2012). Those components include objectives (the management goals and constraints), alternative actions (the different management actions available to decision makers), predictive models (predictions of the impacts of the different actions on the objectives), and optimization (a method for identifying the optimal action within the set considered). Structured decision making focuses on recognizing and isolating the appropriate functions of policy (i.e., objective setting) versus science (i.e., model development and optimization) in decision making, and on making decisions that are transparent, replicable, and robust to uncertainty.

We describe the development and application of a structured decision making framework designed specifically to address 2 key impediments to the Florida Non-migratory Population reintroduction decision: uncertainty and multiple objectives. Our goal was to develop a framework that could be used by FWC to decide whether to petition the IWCRT for captive-reared chicks with which to continue the whooping crane release program in Florida. Further, we considered not just whether more chicks should be released, but the optimal numbers and temporal patterns of release.

STUDY AREA

The FWC carried out releases of whooping cranes at several locations in the Kissimmee Prairie region of central Florida. Release sites were located in Lake, Osceola, and Polk counties, and habitat at the sites consisted of a mix of open grasslands and freshwater marsh. Birds were held in temporary pens at the sites prior to release. After release, birds ranged widely throughout central Florida.

METHODS

Florida Non-Migratory Population Releases

The FWC, in collaboration with partners, released whooping cranes in central Florida from 1993 to 2004. They released 286 cranes over that time. Cranes were bred and raised at the PWRC (66%), at the International Crane Foundation (ICF; 27%), at the Calgary Zoo (6%), and at the San Antonio Zoo (2%) using both parent-rearing and costume-rearing techniques. Cranes were released in winter using a soft-release method. See Nesbitt et al. (1997, 2001) for more details on the reintroduction program.

Scoping the Decision and Working With Experts

Contributing 4 of its own agency personnel to the decision partnership, the FWC chose to include partners from the major breeding centers (PWRC and ICF; 1 member each), the United States Fish and Wildlife Service (USFWS; 1 member), and the University of Florida (1 member) in the decision-making process. All partners informed development of the decision framework, which evolved over a series of face-to-face workshops, conference calls, and by email during 2008. These partners participated as stakeholders by contributing to development of the set of objectives and the weighting of objectives (described below). In addition, these partners also contributed in their capacity as scientific experts through advice on the development of the various models and through formal elicitation of the weight placed on predictions from alternative models of population growth. The authors of this report, with the exception of MJF, did not participate as decision-making partners. Instead, they acted as consultants in leading the team through development of the framework and in developing the technical tools that were used in the process.

Management Objectives

The members of the decision-making team identified 6 objectives relevant to the release of captive-reared whooping cranes in Florida: population establishment, FWC costs, partner costs, alternative restoration project needs, public relations, and information. Since the beginning of the Florida Non-migratory Population restoration effort, the population objective had implicitly served as the fundamental objective. The latter 5 objectives had not been formally specified before this effort. The team members also identified measurable criteria that defined the specific metrics used to measure and model the objectives.

The population establishment objective was to maximize the probability of developing a self-sustaining non-migratory whooping crane population in Florida. The measurable criterion for this objective was the probability that, 100 years after the termination of releases, the Florida Non-migratory Population would be exhibiting positive population growth.

The 2 cost objectives were to minimize the costs of management for FWC and partners. The measurable criterion for FWC cost was dollars spent by FWC over the subsequent 30 years on activities related to the Florida Non-migratory Population effort including release site preparation, maintenance of birds in holding pens, radio monitoring of released birds, recapture of birds for transmitter replacement or health reasons, and monitoring of reproductive activities. The measurable criterion for partner cost was dollars spent by project partners over the subsequent 30 years to produce chicks and ship chicks to Florida.

The alternative restoration project objective was to maximize captive-reared chicks available for other whooping crane restoration efforts (e.g., the Eastern Migratory Population). The measurable criterion for this objective was the number of cohorts (1 cohort = 8 birds) available for alternative restoration efforts over the 20 years following the decision analysis, assuming captive production of 3 cohorts (24 individuals) per year across all rearing facilities.

The public relations objective was to maximize positive public relations reaped by the FWC as an ancillary benefit of the reintroduction of whooping cranes. The established measurable criterion for this objective was based on a constructed scale (i.e., a relative or user-defined scale) of positive public relations, from 0 (low positive public relations) to 1 (high positive public relations).

Finally, the information objective was to maximize learning about whooping crane population behavior, information that would be useful in other efforts to restore this species. This is a fundamentally different concept than the application of information for the internal benefit of a particular management effort (Runge et al. 2011), which would not appropriately be treated as a stand-alone objective. Instead, this objective represents the value placed by stakeholders on information for resolving uncertainties outside of this particular management context. For this objective, the measurable criterion was the probability that the weight on the least optimistic model of population performance, assuming it was correct, would be ≥ 0.95 after 20 years. This worst-case model is described in detail below, but in short, it reflects a situation in which later generations of a reintroduced population perform no better demographically than the captive-bred founders. In other words, this measure reflects the probability that, given the worst-case scenario about reintroduction of whooping cranes from captive founders is correct, we will know that it is correct after 20 years with a high level of confidence. This was deemed a valuable measure because, if this worst-case model is correct, it would suggest that reintroduction of whooping cranes from captive-bred founders is generally unlikely to succeed.

Alternatives

The team considered 29 alternative fixed schedules of releasing birds, varying by the number of cohorts to be released in each year and the number and pattern of years over which birds would be released. A cohort is composed of 8 cranes, a release size that is logistically feasible for the FWC release team and is believed to be conducive to formation of social bonds in the released birds. The team decided upon alternatives that they thought represented a diverse set of feasible options. The team assumed other aspects of the release program would be the same as for earlier releases (i.e., the locations, timing, and other specific methods of release; see Nesbitt et al. 1997, 2001).

1. Alternative 1. No additional releases.
2. Alternatives 2–13. Combinations of 1, 2, or 3 cohorts per year for 5, 10, 15, or 20 years, with releases beginning in the winter of 2009–2010 from 2009 captive production (that is, in the year immediately following completion of the decision-analytic process).
3. Alternatives 14–25. Combinations of 1, 2, or 3 cohorts per year for 5, 10, 15, or 20 years, with releases beginning in the winter of 2019–2020 from 2019 captive production (i.e., a 10-yr delay on releases, with releases beginning 11 yrs after the completion of the decision-analytic process).
4. Alternatives 26–29. Combinations of 1 or 2 cohorts per year for 10 or 20 years, with releases occurring only every other year, beginning in the winter of 2009–2010 from 2009 captive production.

The team developed the first 13 alternatives to take into account a variety of different release strategies that would include no releases, or that would use relatively little (i.e., 1 cohort per year) or nearly all (i.e., 3 cohorts per year) of the expected captive production each year, and for various numbers of years. Under these alternatives, the team assumed that releases would start as soon as possible. The alternatives that allowed for a delay were designed to evaluate the relative costs and benefits of delaying releases until after 10 more years of releases into the Eastern Migratory Population. The last 4 alternatives also attempted to strike a balance with the Eastern Migratory Population reintroduction, but rather than delaying releases, over which time much of the institutional commitment to the releases in Florida may have eroded, these alternatives were designed to allow some releases to the Florida Non-migratory Population beginning immediately and occurring every other year. These alternatives claimed less than half of the captive production over the subsequent 20 years, thus allowing an alternative restoration project to continue to operate in every year.

Modeling for Population Objective

The development of a predictive model for the population objective was substantially more involved than for the other objectives, and is described in greater detail elsewhere (Moore et al. 2012). We summarize here the aspects of that work that are critical for understanding the decision-analytic process we describe. Three models representing competing hypotheses about population response were built relevant to the population objective based on monitoring data gathered over the duration of the Florida Non-migratory Population project. Different models were built to capture the uncertainty in future dynamics of the population especially with respect to the demographic performance of wild-hatched birds. Given that these models resulted in widely different predictions about the probability of success in establishing a self-sustaining population of whooping cranes in Florida (Moore et al. 2012), developing model weights was necessary so we could calculate a weighted average of the model predictions for use in the decision framework. The weights represented the collective judgment of an expert group about the relative evidence for each hypothesis; as a set, these weights represented the magnitude of uncertainty.

Moore et al. (2012) first developed a conceptual population model that modeled transitions among female age and breeding classes for both captive-reared and wild-hatched segments of the population (Fig. 1). This model provided a design template for deriving annual survival rates, breeding class transition probabilities, and productivity rates from data collected on the Florida Non-migratory Population. It also provided the underlying structure for the competing models that they analyzed via simulation. The authors analyzed radio-telemetry data from the captive-reared segment of the flock to estimate the parameters of this model.

Moore et al. (2012) next constructed 3 alternative population models using sets of available parameter estimates. Each model simulated individual female birds in the population and tracked them through time in response to hypothesized survival and productivity rates, periodic releases of captive-reared female chicks into the population, and random effects. The models differed in how vital rates for the 2 segments of the population (captive-reared and wild-hatched) resembled or differed from each other. In all 3 models, they assumed survival and productivity parameters estimated solely from the captive-reared segment of the population to apply to simulated future captive-reared birds. In the baseline model (model 1), they assumed these estimated rates also applied to simulated wild-hatched birds.

In an alternative model (model 2), Moore et al. (2012) assumed that survival and productivity rates of the wild-hatched segment more closely corresponded to those of the only wild flock in existence, the Aransas–Wood Buffalo Population. Thus, they applied estimated rates for the wild population to simulated wild-hatched birds. The authors applied the estimated overall survival rate from the Aransas–Wood Buffalo Population (model CAAE; Link et al. 2003) to all age and breeding classes of wild-hatched birds. Simulations also incorporated year-to-year variability in survival as well as estimation uncertainty (McGowan et al. 2011). Therefore, the survival rate applied to wild-hatched birds varied from year to year and among simulation runs. For productivity, Moore et al. (2012) assumed that captive-reared and wild-hatched birds shared a common rate of transition into the breeder classes (i.e., probability that an unpaired female forms her first pair bond). However, they used the Aransas–Wood Buffalo estimate of average per-breeder productivity rate (0.33; 1938–2001 period) in place of breeding class-specific productivity rates estimated from the captive-reared data. As for the survival rate parameter, they incorporated annual stochastic variation and parameter uncertainty in simulations of recruitment rate in wild-hatched birds, thus recruitment rate varied among years and simulation runs.

A third model, or class of models, considered an Allee-type effect (Allee 1931, 1938), in which a population requires a critical mass of individuals in order to grow. Allee effects may be expected in small, establishing populations (Courchamp et al. 1999, Stephens et al. 1999) and various mechanisms could contribute to an Allee effect within a whooping crane flock. For example, a low population density may reduce availability of mates, obscure behavioral cues among potential breeders or foraging birds, or divert energies into sentinel and predator avoidance behaviors (Courchamp et al. 1999). Magnification of the effect of inbreeding depression at low population size is another possible Allee mechanism (Stephens et al. 1999). Model 3 of Moore et al. (2012) does not propose an Allee mechanism, it simply suggests that productivity is greater above a threshold density of breeders. Under model 3, they maintained survival rates for captive-reared and wild-hatched birds exactly as in model 2. However, the productivity rate they applied to simulated wild-hatched birds depended on a population size condition. When the number of breeding-age females (all females $\geq$2 yrs, from both population segments) exceeded a fixed threshold size (B_T), they applied the Aransas–Wood Buffalo estimate of productivity to wild-hatched breeding-class birds. Otherwise, wild-hatched birds received the productivity rate estimate derived from captive-reared birds. By varying the value of B_T, the model could be made to resemble model 2 ($B_T = 0$) or model 1 ($B_T \rightarrow \infty$).

The model set thus portrayed a plausible range of population responses consistent with uncertainty about performance of wild-hatched birds: performance of wild-hatched birds is similar to that of captive-reared birds (model 1), performance of wild-hatched birds is always significantly better than that of captive-reared birds (model 2), or performance of wild-hatched birds relative to captive-reared birds is conditional on number of breeding-age females exceeding some size threshold (model 3). However, goodness-of-fit assessment of the 3 models (Moore et al. 2008, 2012) did not result in any compelling evidence to favor 1 model over the others because of the scarcity of observations on wild-hatched birds.

Moore et al. (2012) simulated population growth under each model, for each alternative action, from a common population starting point in 2008, with 10,000 replicates. Under model 3, they conducted simulations for each of 8

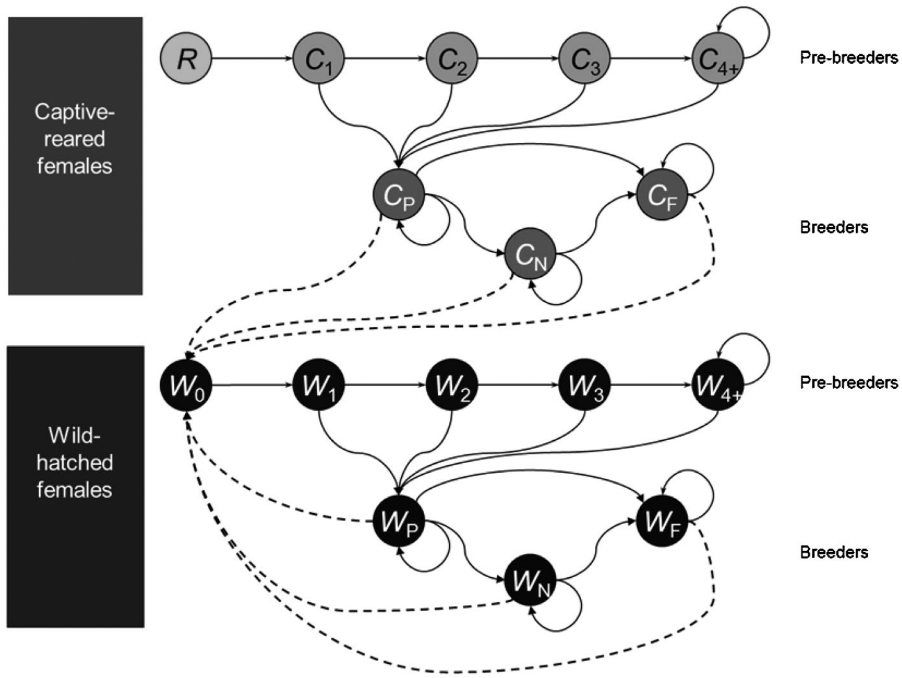

Figure 1. Female-based population model for projecting dynamics of the Florida Non-migratory Whooping Crane Population through time. Birds released (R) into the population survive annually into successive age classes of unpaired birds (C_1, C_2, C_3, and C_{4+}), and unpaired birds may themselves survive and become paired (C_P). Paired birds may then survive and produce no young, nestling(s) that do not fledge, or fledgling(s). Likewise, birds that have produced only nestlings previously (C_N) may become fledgling producers (C_F). All fledglings produced by any of these types of breeders become the 0 age class of the wild-hatched segment (W_0). Pathways within the wild-hatched segment are similar to the captive-reared segment, although the rates of transition may differ between the 2 segments.

different settings of the B_T parameter: 5, 10, 15, 20, 25, 30, 40, and 50 females. All simulations were conducted over a fixed 131-year time frame, a point 100 years beyond the latest possible release under any scenario (i.e., those incorporating a 10-yr delay followed by 20 yrs of releases). In each simulation, they computed the population trend (simple regression of population size) over the last 20 years of the 131-year time frame, and, for each set of 10,000 simulations, determined the proportion of simulations for which this trend was positive.

Uncertainty with respect to the different predictions made by the models in Moore et al. (2012) made developing model weights necessary so a weighted-average prediction could be calculated for use in the decision framework. Model weights can be thought of (in a Bayesian sense) as the prior belief in the veracity of each model. We developed model weights in an expert elicitation exercise at 1 of the 2008 workshops using a modified Delphi method (MacMillan and Marshall 2006). We began by discussing in detail the biological motivation and development of each model, the lack of empirical evidence supporting 1 model over another, and the predictions made by each model. Then we asked each participant to place a probability on each of the models. We initially asked the experts to place weight on all 10 candidate models (model 1, model 2, and model 3 with 8 different values of B_T). We conducted this exercise with each participant working alone. We gathered these results from each participant and then displayed them to the group to motivate discussion. After discussion, the group elected to go through the exercise a second time, but this time in 2 steps. First, individuals placed weight on model 1, model 2, and model 3, where the focus was on the experts' belief in the basic dynamics described by each model. In a second step, each expert then allocated the weight that he or she had placed on model 3 among the 8 different versions of model 3 (i.e., the 8 different threshold population sizes). Again, we tabulated the weights and the group discussed the results. Individual experts revisited these weights and went through the exercise a third time. After the third iteration, the panel decided that no further revision was necessary. We retained the final individual weights and the average across experts.

Modeling for Information Objective

We derived the model for the information, or learning, objective from the models for the population objective. The predictive model for the information objective measured how likely data yielded by each of the alternative release options could convincingly demonstrate within 20 years that population establishment would not succeed under the assumption that model 1 was the best representation of the system. The rationale for such a criterion was that, if reintroduction was truly not a viable means to establish a whooping crane population, then release alternatives that indicated that fact sooner rather than later had greater value from a learning standpoint. To estimate this criterion, we simulated model 1 1,000 times for each decision alternative. Over each successive year in the simulation, we recorded the directional change (decrease, no change, or increase) for each of 3 composite states: wild-hatched age = 0, wild-hatched pre-breeders >0 years, and wild-hatched breeders. The focus was on the wild-hatched states because the model predictions differed for those states but not for the captive-reared states.

The simulations tracked model confidence weights associated with the assumed true generating model (model 1) and with 2 competing models, model 2 and model $3/B_T = 20$ (the version of model 3 that was given the greatest weight in the model weighting exercise). In other words, we simulated the process by which a true model could be identified from a set of 3 uncertain but plausible candidate models. We used Bayesian updating to update the model weights each year where the new model weight in year $t + 1$ was equal to the model weight in year t multiplied by the likelihood of the model, given the data (i.e., the observation from the underlying true generating model). We set the weights as equal in year 1 (1/3 assigned to each model). We calculated the likelihoods by simulating forward from the current state 1,000 times under each of the 3 models, and calculating the probability each year of observing a particular pattern of changes in the 3 composite states (3 directional changes for each of 3 composite states yields 9 possible observable patterns under each model). The model output was the probability of attaining a model weight of $\geq$0.95 on model 1 (the assumed true model) at 2029 (i.e., 20 yrs from 2009).

Modeling for Additional Objectives

Cost objective 1: FWC costs.—The first cost objective was the portion of costs that were incurred by the FWC including costs covered by the annual grant to FWC from the USFWS. We estimated costs over a 30-year period, which was the time span of the longest-running release scenario. We estimated annual fixed costs at $300,000/year including $150,000/year contributed by the USFWS grant and another $150,000/year contributed by FWC. We assumed fixed costs applied even in the case of no further releases, as activities in support of bird monitoring and recovery would nevertheless continue for the existing population. We estimated annual release-specific costs at $75,000 for 1 cohort, $85,000 for 2 cohorts, and $95,000 for 3 cohorts. In addition, the model assumed 2 additional years of fixed costs ($600,000) related to re-start activities associated with any alternative involving a delay in releases, because of the expected decrease in efficacy with a loss of institutional experience after suspension of those activities.

Cost objective 2: Partner costs.—The second cost objective was the portion of costs that were incurred by partners for the breeding, rearing, and shipping of chicks for release in Florida. We estimated per-bird costs at $15,000 at the PWRC breeding facility and $18,000 at the ICF breeding facility. Given relative flock sizes, we assumed that PWRC would supply two-thirds of the birds and ICF would supply the remaining third. In addition, we estimated shipping costs at $15,000 per cohort.

Alternative restoration project objective.—Based on past production, we assumed that 3 cohorts (24 birds) would represent virtually the entire captive production available for release barring a major improvement in captive productivity and survival. The model for this objective calculated the number of cohorts available to alternative whooping crane restoration projects (Eastern Migratory Population and/or others) over the next 20 years (out of 60 expected to be produced over that time frame). This seemed to the team to be a reasonable planning horizon given the expected length of Eastern Migratory Population releases and the ability to make predictions about the production at captive breeding facilities in the future.

Public relations objective.—This objective, representing the positive public relations for FWC reaped as part of the reintroduction program, was simply modeled with a 0 or 1 index. Any alternatives involving additional reintroductions resulted in an index score of 1, and the termination of reintroductions resulted in an index score of 0. We based these predictions on expert knowledge represented by FWC managers on the team.

SMART Analysis

Given the multi-objective nature of the problem, quantitatively establishing the tradeoffs among objectives was necessary to determine the optimal action. We used the Simple Multi-Attribute Rating Technique (SMART; Edwards 1977, Goodwin and Wright 2004) to conduct the tradeoffs analysis.

The first step was to develop objective weights, which reflected the relative importance of each objective, using the swing weighting technique (Goodwin and Wright 2004). Swing weighting attempts to develop preferences specific to the given decision context. Weights are not abstract, but measure how much stakeholders value an objective given how much the alternatives differ over that objective. As a conceptual example, stakeholders may be more focused on costs if their alternatives have costs ranging from $10,000 to $20,000 than if their alternatives have costs ranging from $10,000 to $11,000.

To develop swing weights, we asked representatives of the decision-making agencies to imagine a hypothetical alternative under which all of the objectives were at their least-preferred level, given the range in the true alternatives. This theoretical option would have the highest FWC costs, highest partner costs, lowest number of birds available for alternative restoration projects, lowest probability of population establishment, poorest public relations performance, and lowest information gain. We then asked each representative to select which objective they would move (swing) from the least-preferred to the most-preferred value if they could only choose 1. The first objective identified was given a rank of 1, the second a rank of 2, and so on until all 6 objectives had been ranked. Each representative then ranked the objectives between 0 and 100, with 100 given to the objective that received rank 1. The 0–100 ratings reflect relative importance of the objectives according to that stakeholder. As in the model weighting exercise, we conducted the objective weighting exercise multiple times to ensure that participants understood the technique and had a chance to reflect on the results as a group before we determined the final weights. We normalized each respondent's ratings to the sum of his/her ratings. We computed the final consensus weight for objective j, W_j, by averaging normalized ratings for the objective over all respondents.

Next, we normalized the scores within each objective to a 0–1 scale with the most desirable outcome for a given objective scoring a 1 and the least scoring a 0. We computed the normalized score for alternative action i relative to objective j based on the original score ($S_{i,j}$) as

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

for objectives where the desired direction of the original scores was high (i.e., alternative restoration project objective, population objective, public relations objective, and information objective), or alternatively

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

where the desired direction of the original scores was low (i.e., FWC and partner cost objectives).

We then calculated a final score for alternative i (F_i) as the sum over all objectives (j) of the product of the swing weight (W_j) and the normalized scores:

$$F_i = \sum_j W_j \times N_{i,j}$$

Finally, we also conducted an analysis to examine the sensitivity of the final recommendation to cross-stakeholder variation in objective weights. We achieved this by using the weights of each individual expert rather than the consensus (mean) weights to complete the analysis.

RESULTS

The results of population simulations revealed 2 clear patterns (Moore et al. 2012; Fig. 2). First, outcomes were sensitive to model uncertainty. Under model 1, all decision alternatives resulted in nearly 0 chance of successful population establishment, whereas under model 2, all decision alternatives yielded very high ($\geq$0.90) probabilities of population establishment success. Second, whereas the outcome was not sensitive to the release alternative under either model 1 or 2, the outcome was clearly sensitive to the alternative for the different versions (different levels of B_T) of model 3. For example, if a threshold of 20 breeding-status females is required to trigger greater production in the population, then decisions that release more birds over time are far more likely to establish a population than those that release fewer.

On average, our experts gave 34.4% of the model weight (their belief in the model) to model 1 (Table 1). By contrast, they gave only 6.3% of the model weight to model 2. For the remaining weight, placed on model 3, the experts had the greatest belief in a value of B_T of 20 females. The result of the relatively low weight for model 2 was an overall lower prediction of population establishment success (Table 2), which varied from 0.09 to 0.411 under different alternatives.

The result of the SMART analysis indicated that a different alternative was preferred when we considered all objectives than if we considered any 1 individual objective alone (Table 3). Overall, the alternative with the greatest composite score (F_i) was 3 cohorts per year for 10 years with an immediate start (Table 3; Fig. 3). This strategy was followed by alternatives of 3 cohorts per year for 15 years, 2 cohorts per year for 15 years, and 2 cohorts per year for 10 years, each with an immediate start. Also ranking high were alternatives

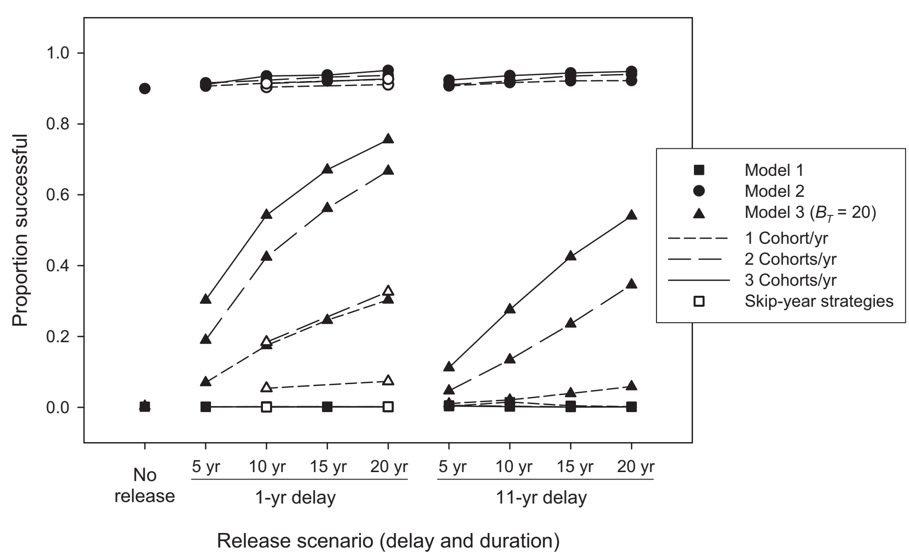

Figure 2. Reproduced from Moore et al. (2012). Simulation outcomes (proportion of simulations yielding positive population growth) for alternative release strategies under 3 alternative models of population growth for the Florida Non-migratory Whooping Crane Population. Time delay until the first release and duration of release are displayed on the horizontal axis. Outcomes are plotted for 1 (short dashes), 2 (medium dashes), or 3 (solid line) cohorts per year under model 1 (squares), model 2 (circles), and case $B_T = 20$ of model 3 (triangles). Under models 1 or 2, the outcome is insensitive to the decision, resulting either in extirpation (model 1) or establishment (model 2) in every case. Under model 3, the outcome is highly sensitive to the release decision, and the response pattern reveals greater probability of success with intensive release activity that occurs earlier and persists longer.

Table 1. Results from the third and final iteration of expert elicitation of model weights (100 = full belief) for models predicting Florida Non-migratory Whooping Crane Population behavior. Models differed in assumptions of survival and productivity rates of wild-hatched birds: model 1 (M1; wild-hatched = captive-reared rates), model 2 (M2; wild-hatched = Aransas–Wood-Buffalo rates), and 8 versions of model 3 (M3; wild-hatched survival = Aransas–Wood-Buffalo survival but wild-hatched productivity = Aransas–Wood-Buffalo productivity only over some Allee threshold, B_T). We report individual experts' scores along with averages across experts. We used the average results from the third iteration to develop predictions for the population objective.

		M 3								
Expert	M 2	$B_T = 5$	$B_T = 10$	$B_T = 15$	$B_T = 20$	$B_T = 25$	$B_T = 30$	$B_T = 40$	$B_T = 50$	M 1
1	20	0	0	0	0	0	0	0	0	80
2	10	0	0	0	50	40	0	0	0	0
3	10	10	10	10	10	10	10	10	10	10
4	0	0	0	0	5	5	10	10	20	50
5	0	5	5	5	15	15	10	10	10	25
6	0	0	0	4	8	16	8	4	0	60
7	0	0	10	20	40	10	0	0	0	20
8	10	0	0	0	0	0	20	20	20	30
Average	6.3	1.9	3.1	4.9	16.0	12.0	7.3	6.8	7.5	34.4

of 2 or 3 cohorts per year for 5 or 20 years with an immediate start. However, immediate releases of 1 cohort per year for any number of years, or any of the alternatives involving skipping (i.e., alternatives allowing for a split of captive-reared birds between the Florida Non-migratory Population and the Eastern Migratory Population) also ranked higher than alternatives involving delayed releases or no additional releases. The alternative involving no additional releases ranked 21st out of 29 alternatives. This was a lower-ranked alternative than anything but delayed releases of 1 or 2 cohorts. The preferred alternatives were a result of the pattern of objective weights; overall the highest weight was placed on the population objective (Table 4). This was the most important objective for every stakeholder.

Table 2. Model predictions for each of 6 objectives relevant to management of the Florida Non-migratory Whooping Crane Population for each of the 29 decision alternatives. Alternatives are defined by the years of releases (duration), the number of cohorts to release each year (cohorts) and whether the releases would start in the year immediately after completion of the analysis (delay = 1) or would be delayed 10 additional years (delay = 11). Objectives include the costs to the Florida Fish and Wildlife Conservation Commission, costs to other partners in the project, the number of cohorts available for alternative restoration projects, the public relations benefits, probability of meeting the population objective, and the probability of obtaining information over time about whether the worst case scenario population model is true.

Release alternative								
Delay (yr)	Duration (yr)	Cohorts	FWC[a] cost (million \$)	Partner cost (million \$)	Alternative restoration (no. of cohorts)	Public relations (0–1 scale)	Population (probability)	Information (probability)
	0	0	\$9	\$0	60	0	0.090	0.657
1	5	1	\$9.375	\$0.715	55	1	0.119	0.758
1	5	2	\$9.425	\$1.430	50	1	0.154	0.802
1	5	3	\$9.475	\$2.145	45	1	0.191	0.865
1	10	1	\$9.750	\$1.430	50	1	0.152	0.785
1	10	2	\$9.850	\$2.860	40	1	0.232	0.905
1	10	3	\$9.950	\$4.290	30	1	0.289	0.927
1	15	1	\$10.125	\$2.145	45	1	0.175	0.795
1	15	2	\$10.275	\$4.290	30	1	0.287	0.917
1	15	3	\$10.425	\$6.435	15	1	0.358	0.937
1	20	1	\$10.500	\$2.860	40	1	0.193	0.795
1	20	2	\$10.700	\$5.720	20	1	0.332	0.925
1	20	3	\$10.900	\$8.580	0	1	0.411	0.934
11	5	1	\$9.975	\$0.715	55	1	0.101	0.721
11	5	2	\$10.025	\$1.430	50	1	0.117	0.720
11	5	3	\$10.075	\$2.145	45	1	0.137	0.806
11	10	1	\$10.350	\$1.430	50	1	0.113	0.699
11	10	2	\$10.450	\$2.860	40	1	0.145	0.759
11	10	3	\$10.550	\$4.290	30	1	0.194	0.792
11	15	1	\$10.725	\$2.145	50	1	0.116	0.677
11	15	2	\$10.875	\$4.290	40	1	0.178	0.745
11	15	3	\$11.025	\$6.435	30	1	0.249	0.805
11	20	1	\$11.100	\$2.860	50	1	0.122	0.701
11	20	2	\$11.300	\$5.720	40	1	0.216	0.752
11	20	3	\$11.500	\$8.580	30	1	0.303	0.785
1	10 (A)[b]	1	\$9.375	\$0.715	55	1	0.117	0.721
1	10 (A)	2	\$9.425	\$1.430	50	1	0.154	0.788
1	20 (A)	1	\$9.750	\$1.430	50	1	0.129	0.725
1	20 (A)	2	\$9.850	\$2.860	40	1	0.199	0.826

[a] Florida Fish and Wildlife Conservation Commission.
[b] A indicates releases would occur only every other year during the 10 or 20 year period.

Table 3. Normalized model predictions for each of 6 objectives relevant to management of the Florida Non-migratory Whooping Crane Population, and the average score (weighted by objective weights) and rank for each of 29 release alternatives. Alternatives are defined by the years of releases (duration), the number of cohorts to release each year (cohorts) and whether the releases would start in the year immediately after completion of the analysis (delay = 1) or would be delayed 10 additional years (delay = 11). Objectives include the costs to the Florida Fish and Wildlife Conservation Commission, costs to other partners in the project, the number of cohorts available for alternative restoration projects, the public relations benefits, probability of meeting the population objective, and the probability of obtaining information over time about whether the worst case scenario population model is true. For the normalized values, a value of 1 indicates most preferred.

Release alternative										
Delay (yr)	Duration (yr)	Cohorts	FWC[a] cost	Partner cost	Alternative restoration	Public relations	Population	Information	Weighted average	Rank
	0	0	1.00	1.00	1.00	0.00	0.00	0.00	0.419	21
1	5	1	0.85	0.92	0.92	1.00	0.09	0.36	0.499	12
1	5	2	0.83	0.83	0.83	1.00	0.20	0.52	0.542	8
1	5	3	0.81	0.75	0.75	1.00	0.31	0.74	0.598	7
1	10	1	0.70	0.83	0.83	1.00	0.19	0.46	0.508	11
1	10	2	0.66	0.67	0.67	1.00	0.44	0.89	0.625	4
1	10	3	0.62	0.50	0.50	1.00	0.62	0.96	0.657	1
1	15	1	0.55	0.75	0.75	1.00	0.26	0.49	0.496	13
1	15	2	0.49	0.50	0.50	1.00	0.61	0.93	0.628	3
1	15	3	0.43	0.25	0.25	1.00	0.83	1.00	0.651	2
1	20	1	0.40	0.67	0.67	1.00	0.32	0.49	0.472	15
1	20	2	0.32	0.33	0.33	1.00	0.75	0.96	0.616	6
1	20	3	0.24	0.00	0.00	1.00	1.00	0.99	0.619	5
11	5	1	0.61	0.92	0.92	1.00	0.03	0.23	0.416	22
11	5	2	0.59	0.83	0.83	1.00	0.08	0.23	0.411	23
11	5	3	0.57	0.75	0.75	1.00	0.15	0.53	0.460	16
11	10	1	0.46	0.83	0.83	1.00	0.07	0.15	0.373	27
11	10	2	0.42	0.67	0.67	1.00	0.17	0.36	0.398	24
11	10	3	0.38	0.50	0.50	1.00	0.32	0.48	0.426	20
11	15	1	0.31	0.75	0.83	1.00	0.08	0.07	0.331	28
11	15	2	0.25	0.50	0.67	1.00	0.28	0.31	0.385	26
11	15	3	0.19	0.25	0.50	1.00	0.50	0.53	0.444	18
11	20	1	0.16	0.67	0.83	1.00	0.10	0.16	0.320	29
11	20	2	0.08	0.33	0.67	1.00	0.39	0.34	0.390	25
11	20	3	0.00	0.00	0.50	1.00	0.67	0.46	0.442	19
1	10 (A)[b]	1	0.85	0.92	0.92	1.00	0.08	0.23	0.476	14
1	10 (A)	2	0.83	0.83	0.83	1.00	0.20	0.47	0.534	10
1	20 (A)	1	0.70	0.83	0.83	1.00	0.12	0.24	0.446	17
1	20 (A)	2	0.66	0.67	0.67	1.00	0.34	0.60	0.539	9

[a] Florida Fish and Wildlife Conservation Commission.
[b] A indicates releases would occur only every other year during the 10 or 20 year period.

Other overall high-ranked objectives were FWC cost, alternative restoration efforts, and information. Partner costs and public relations ranked fifth and sixth most important when averaged across all stakeholders.

Our sensitivity analysis suggested that the final preferred alternative was relatively insensitive to cross-stakeholder variation in objective weights. In fact, examination of the 8 individual stakeholders showed that 4 of the stakeholders would have also preferred the overall preferred alternative (Table 4). In addition, 3 stakeholders would have ranked the overall preferred alternative (immediate releases for 10 yrs of 3 cohorts per year) second, third, or fourth (the top-ranked alternatives for these stakeholders all involved release of 3 cohorts per year for either 15 or 20 yrs, with an immediate start). Only 1 of the stakeholders did not prefer an alternative that included releases of 3 cohorts per year for 10, 15, or 20 years with an immediate start. This stakeholder preferred the alternative involving release of 2 cohorts per year for 10 years with an immediate start, and ranked the overall preferred alternative (3 cohorts per year for 10 yrs, with an immediate start) ninth.

DISCUSSION

The critical uncertainty captured in the population modeling effort involves the demographic performance of wild-hatched birds. Fourteen years after the first releases into the Florida Non-migratory Population, we did not have adequate information to conclude that wild-hatched birds survive better than their captive-reared parents, though early evidence pointed in that direction (Moore et al. 2008). We had essentially no information to evaluate the potential reproductive success of wild-hatched birds, as these birds had only just begun to exhibit breeding behavior. In addition, the low and declining sample size restricted the potential for learning about breeding success of wild-hatched birds and this was expected to continue without additional releases especially because males were underrepresented in the population (a factor not fully captured in our female-only model, except indirectly via presumably reduced reproductive rates of captive-reared females).

Resolving uncertainty about the performance of wild-hatched birds relative to their captive-reared parents is

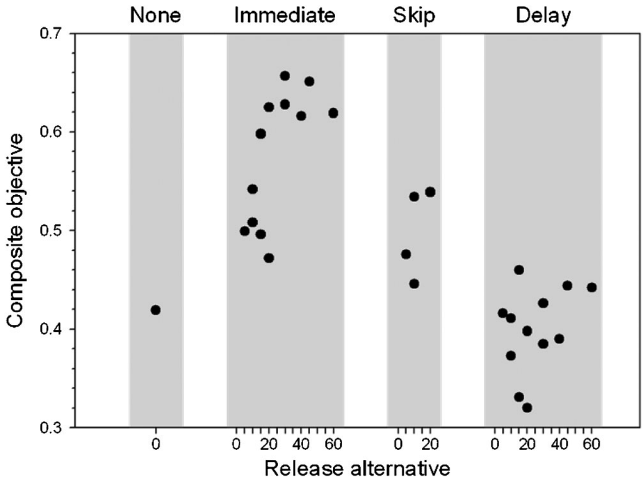

Figure 3. Composite objective score for decision alternatives for management of the Florida Non-migratory Whooping Crane Population, in each of 4 broad categories, including none (no further releases), immediate (begin releases immediately), skip (conduct releases only every other year), and delay (wait 11 yrs to begin releases). Within each category, the *x*-axis indicates the total number of cohorts released (combinations of years and numbers of cohorts released per year).

critical to determining whether restoration of whooping crane populations is feasible. Based on the performance of captive-reared birds in the Florida Non-migratory Population (expressed in all of the models) and early indications of the performance of captive-reared birds in the Eastern Migratory Population (extremely low reproductive success to date; Urbanek et al. 2010), captive-reared birds do not perform well post-release. It is possible that either captive-reared birds in the Eastern Migratory Population could prove to be better performers over time or with different management approaches or that captive-reared birds in a novel reintroduction program would perform better. But barring these possibilities, success of any whooping crane restoration effort appears dependent on the proposition of wild-hatched birds performing better than their captive-reared parents. Indeed, evidence from the Eastern Migratory Population, which suffers from poor reproductive success, suggests that all challenges in whooping crane reintroduction have not yet been solved (Urbanek et al. 2010, Converse et al. 2012).

Although we assumed in model 2 and model 3 that wild-hatched birds would perform as well as birds from the Aransas–Wood Buffalo Population, wild-hatched birds did not need to perform demographically at this level to attain a high probability of reintroduction success. The critical uncertainty is not whether the wild-hatched birds do as well as the Aransas–Wood Buffalo birds, but whether they do sufficiently better than their captive-reared parents to sustain the Florida Non-migratory Population. In an earlier analysis (not presented here), results indicated that reproductive success within 5% of that attained by the Aransas–Wood Buffalo Population would lead to >75% probability of success under some alternative release scenarios.

In addition to uncertainty, the multiple-objective nature of this decision increased its difficulty. The preferred alternative did not perform best on the obvious objective (i.e., the population objective). Both the population and information objectives (Table 3) drove the results toward favoring alternatives involving continued releases and the most intensive release alternatives (3 cohorts per year for 20 yrs, beginning immediately) performed very well on these objectives. However, the alternative restoration objective and the FWC cost objective, which also received relatively high weight, favored alternatives with no further releases. Therefore, the final selection of 3 cohorts per year for 10 years represents a compromise option between these different objectives. We also note, based on the sensitivity analysis, that the decision was rather insensitive to cross-stakeholder variation in the objective weights, suggesting that the compromise option was not one where everyone loses a little but instead represented a truly shared preference across stakeholders.

Table 4. Weights assigned to each of 6 objectives relevant to management of the Florida Non-migratory Whooping Crane Population, determined by averaging over individual respondents' ratings (overall), and the resulting highest-ranked decision alternative, as well as, for individual stakeholders, their objective weights, their highest-ranked alternative, and the individual ranks, given individual weights, of the overall preferred alternative. Objectives include the costs to the Florida Fish and Wildlife Conservation Commission, costs to other partners in the project, the number of cohorts available for alternative restoration projects, the public relations benefits, probability of meeting the population objective, and the probability of obtaining information over time about whether the worst case scenario population model is true.

Stakeholder[a]	FWC[b] cost	Partner cost	Alternative restoration	Public relations	Population	Information	Highest ranked[c]	Individual rank of overall preferred[d]
Overall	0.16	0.10	0.16	0.03	0.39	0.16	1/10/3	
1	0.03	0.26	0.30	0.00	0.33	0.08	1/10/2	9
2	0.33	0.11	0.11	0.04	0.37	0.04	1/10/3	1
3	0.10	0.06	0.26	0.00	0.32	0.26	1/10/3	1
4	0.23	0.09	0.11	0.02	0.45	0.09	1/15/3	2
5	0.21	0.10	0.14	0.03	0.34	0.17	1/10/3	1
6	0.15	0.02	0.04	0.07	0.36	0.36	1/20/3	3
7	0.21	0.13	0.17	0.02	0.43	0.04	1/10/3	1
8	0.05	0.02	0.12	0.07	0.49	0.24	1/20/3	4

[a] Order of stakeholders does not necessarily accord with order of experts in Table 1, though participants in the process contributed both as scientific experts and as decision stakeholders.
[b] Florida Fish and Wildlife Conservation Commission.
[c] Alternatives are given as delay (yr)/duration (yr)/cohorts (no.).
[d] The rank of the alternative that was highest ranked under the overall (mean) analysis (i.e., 1/10/3) when analysis was conducted based on that individual stakeholder's objective weight.

Although the FWC adopted the results of this analysis, the IWCRT in turn recommended that all releases to the Florida Non-migratory Population be terminated. The IWCRT cited 4 major concerns in their final recommendation (T. Stehn, United States Fish and Wildlife Service, unpublished report). These included that 1) the population modeling work predicted only a 41% chance of achieving successful population establishment under the most intensive release strategy of 3 cohorts per year for 20 years starting immediately (Table 2), 2) the number of whooping cranes available for release would be less than 3 cohorts or 24 birds per year (presumably because the IWCRT was committed to ongoing releases for the Eastern Migratory Population) and with fewer birds released the predicted probability of successful establishment was even lower, 3) periodic drought in Florida rendered it unlikely that reproduction in the wild would ever be adequate, and 4) crane habitat in Florida was expected to decline under pressure from development. Although the FWC rather than the IWCRT was the client for the analysis described herein, analyzing each of these concerns in the context of decision analysis may be useful. Taking that approach, the first 2 concerns relate primarily to the IWCRT's objectives. Specifically, the concern that 41% probability of success was overly low would suggest that the IWCRT did not place high value on the ability to swing that probability from 9% to 41% and so placed low weight on this objective. In addition, the IWCRT seemed to perceive the alternative restoration projects as a constraint that must be met rather than as an objective that would be maximized given optimal tradeoffs, and so were not willing to consider alternatives that dedicated all captive production to the Florida Non-migratory Population.

The latter 2 concerns cited by the IWCRT appear to relate to belief in the models and specifically suggest that the IWCRT did not have high confidence that past demographic behavior of the population (as captured by the demographic estimates used to build the population models of Moore et al. 2012) would adequately characterize future behavior. The productivity rates projected by the models for captive-reared birds reflect whatever factors limited performance over the 1993–2007 period of analysis. Possible factors included demographic imbalance of sexes, inbreeding-related reproductive dysfunction, unfavorable climatic conditions, and loss of habitat. In particular, we note that water levels were suboptimal for whooping crane breeding during several of the years over which we estimated reproduction (Spalding et al. 2009). However, the population models could not readily account for continuing loss of habitat in Florida. In most cases, a population of an endangered species would be protected from habitat loss by critical habitat designation, but the Florida Non-migratory Population was designated as a Nonessential Experimental Population (Lewis and Finger 1993) and so does not receive such protection. This strongly suggests that all future attempts to reintroduce whooping cranes should carefully consider not just habitat available at the outset of the reintroduction but expected habitat availability over the long-term. From 1974 to 2003, suitable crane habitat in Florida declined an average of 16.6% during each of the 10-year increments (Nesbitt and Hatchitt 2008). As of 1 March 2012, the Florida Non-migratory Population consisted of 19 birds (8 males, 11 females). Three of 11 birds that have fledged in the wild are still accounted for. No wild-fledged birds have successfully hatched chicks.

Although other formal applications of decision analysis have been used to inform reintroduction decisions (e.g., Maguire 1986, Maguire et al. 1988, Bearlin et al. 2002, Tenhumberg et al. 2004, VanderWerf et al. 2006) the primary focus has generally been on uncertainty as the major impediment to these decisions. Significantly, we believe this to be the first published application of fully realized multiple objective decision analysis (Keeney and Raiffa 1976) to a reintroduction decision. Our application makes formal use of multiple-objective methods in recognition of the fact that managers of endangered species are frequently weighing multiple different considerations. And in fact, we did find that the outcome was different than if we had only considered the population establishment objective, which was an implicit objective from the start of the effort. The preferred alternative was different than if any single objective (aside from the public relations objective, which contained very little power to distinguish among alternatives) had been considered in isolation. This is a critical point and illustrates the value of explicit consideration of tradeoffs. Considering the larger set of objectives forced a more thorough analysis of the problem and the tradeoffs managers were facing. We suggest that other managers contemplating reintroduction decisions consider multiple objective methods for rendering their decisions in a more deliberative and transparent fashion.

MANAGEMENT IMPLICATIONS

Our analysis of this decision problem recommended ongoing reintroductions, specifically release of 3 cohorts per year for 10 years starting immediately. The IWCRT did not choose to allocate chicks to this release program and the population has declined since this analysis was completed. However, FWC has continued to monitor the population to increase our understanding of the ecology of reintroduced whooping cranes. Ongoing analysis and integration of these data into decision-making processes in support of current reintroduction efforts for the Eastern Migratory Population and the newly established Louisiana Non-Migratory Population will be critical.

Development of a decision-analytic structure requires a collaborative effort amongst managers, scientists, and decision-analytic experts. Our collaborative effort resulted in an analysis that proved to be useful for framing, solving, and communicating the outcome and rationale for the decision. Structured approaches to decision making should be adopted more widely in reintroduction decisions. This recommendation echoes the general call by a host of other authors for a more structured approach to reintroduction decisions (Maguire 1986, Burgman et al. 1994, Possingham 1996, McCarthy et al. 2012, Nichols and Armstrong 2012, Converse et al. 2013).

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