Trading off short-term and long-term risk: minimizing the threat of Laysan Duck extinction from catastrophes and sea-level rise

A Case Study from the Structured Decision Making Workshop
January 25–29, 2010
National Conservation Training Center, Shepherdstown, WV, USA

Authors: Michelle Reynolds[1], Conor McGowan[2], Sarah J. Converse[2], Brady Mattsson[2], Jeffrey S. Hatfield[2], Andrew McClung[3], Loyal Mehrhoff[4], Jeffrey R. Walters[5], and Kim Uyehara[6]

Decision Problem

Conservation of oceanic island species presents many ecological and logistical challenges. The Northwestern Hawaiian Islands (NWHI) include 300,000 km^2 of ocean waters and 10 groups of sub-tropical islands and atolls of high conservation value. Designated as Papahanaumokuakea Marine National Monument, the islands provide habitat for four endangered species of terrestrial birds. Despite their protected status, many of these species are faced with the ongoing threat of extinction due to stochastic catastrophes such as disease, invasive mammal introductions, tsunamis, and hurricanes. To reduce the risk that a single catastrophe would lead to extinction, managers propose to restore multiple "insurance" populations on islands currently unoccupied by these species to increase their range and overall numbers.

A longer term threat to NWHI species is sea level rise associated with global climate change. Unfortunately, establishment of populations on multiple low-lying islands is unlikely to provide long-term protection against this threat. On a 50-year time scale, many low-lying NWHI may be partially inundated or totally submerged by rising sea levels. To maintain viable populations of endemic endangered island species in the wild, managers must design and implement a strategy that considers both the longer-term risk of inundation due to sea level rise as well as the ongoing risk of catastrophes, while integrating considerations such as budget limitations, complex logistics, and public opinion of management actions needed to establish species on higher elevation islands.

The set of management actions to balance extinction risks could include translocations of wild populations, habitat restoration, predator eradication (on high elevation sites), development of captive breeding and release programs, or habitat engineering at low elevation sites (e.g., sea walls, dredging, artificial islands). Multiple combinations of these actions could be implemented in space and time. State-dependent decision-making will be necessary to determine the optimal management actions to protect species facing rising sea levels. This decision-making will take place under several sources of uncertainty, including the magnitude and time scale of sea level rise; the cost, uncertainty of success, and political difficulty of management actions such as

[1] U.S. Geological Survey, Pacific Island Ecosystems Research Center, Hawaii National Park, HI, USA
[2] U.S. Geological Survey, Patuxent Wildlife Research Center, Laurel, MD, USA
[3] Los Altos, CA, USA
[4] U.S. Fish and Wildlife Service, Pacific Islands Fish and Wildlife Office, Honolulu, HI, USA
[5] Virginia Polytechnic Institute and State University, Department of Biological Sciences, Blacksburg, VA, USA
[6] U.S. Fish and Wildlife Service, Kauai National Wildlife Refuge Complex, Kilauea, HI, USA

translocation, captive breeding and release, and exotic predator removal on high islands; disease risk; and the genetic viability of both source and translocated populations.

The Laysan Duck (LADU; *Anas laysanensis*) is one of the terrestrial species in the NWHI faced with these ecological threats. For 150 years, the species' distribution was restricted to a single remote island, Laysan Island. Biologists carried out a successful wild translocation from Laysan Island to Midway Atoll, establishing a second viable population 400 miles to the northwest of the source population. Additional translocations to other atolls have been proposed; however, no management plan has been established to deal with the long-term threat of sea level rise. It is expected that much of the current LADU range will be partially submerged within the next 100 years and many of the currently proposed translocation sites will experience inundation as well. There are currently no captive breeding programs managed for reintroduction of the LADU.

The purpose of this project is to identify the optimal sequence of decisions that will protect the LADU in perpetuity in the face of sea level rise and other identified threats. As part of a larger U.S. Geological Survey-funded research project, "Predicting risks of island extinctions due to sea level rise: Model based tools to mitigate terrestrial habitat losses in the Northwestern Hawaiian Islands," we are interested in developing decision-support tools to help Papahanaumokuakea Marine National Monument and recovery managers decide how to best manage endemic birds vulnerable to extinction from sea level rise. Managers will need to work together with state and other federal wildlife agencies to develop and implement a sea level rise management plan. Developing such a plan for the LADU will provide a prototype management tool useful for the three other endangered terrestrial birds in the NWHI (the Laysan Finch, *Telespiza cantans*; the Nihoa Finch, *Telespiza ultima*; and the Nihoa Millerbird, *Acrocephalus familiaris kingi*), as well as seabirds and endangered terrestrial plants.

Background

Legal, regulatory, and political context

The LADU was federally listed as endangered in 1967 (USFWS 1967). The Endangered Species Act (ESA) prohibits the unauthorized take of listed species (e.g., to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, collect, or attempt to engage in any such conduct) and requires that federal actions not jeopardize the survival and recovery of these species. Critical habitat under the ESA has not been designated for the LADU, but a recovery plan has been developed (USFWS 2009). The strategy to delist the LADU consists of:

1. Management and research to reduce known risks and stabilize existing populations (i.e., Laysan and Midway islands).
2. Creation and management of additional self-sustaining populations on other islands through translocation and habitat restoration. The goal is to have at least five stable or increasing LADU populations, each with a minimum of 500 potentially breeding adults. At least two populations should be in the main Hawaiian Islands (MHI). The total wild population should exceed 3,000 potentially breeding adults. Wild populations should be expected to persist for ≥ 100 years, as predicted by population viability analyses.

3. Captive propagation, if necessary, to provide sufficient stock for reintroductions of the LADU in the MHI.
4. Public outreach to ensure that the recovery program for the species especially in the MHI is accepted and supported by local communities.

In addition to federal listing, the LADU is also recognized locally and internationally as an endangered species. The LADU is listed as endangered by the state of Hawai`i. The species also has a NatureServe Heritage Rank of "critically imperiled" and has an IUCN Red List rank of "critically endangered." In addition, the species is protected under the U.S. Migratory Bird Treaty Act, which outlaws unregulated hunting or killing.

However, given this species' apparent inability to coexist with mammalian predators there is a high probability that LADU is a conservation reliant species, even if the above listed recovery/delisting goals are achieved. In general, actions to conserve LADU populations have been without political controversy, and the most suitable islands under consideration for reintroductions are currently uninhabited. However, two issues could become sensitive in the future if and when translocations to the MHI are attempted:

1. Control of invasive predators including rats, mongoose, and feral cats. LADU are unlikely to withstand predation from any of these invasive predators, and the control of feral cats or dogs could be controversial. Additionally the use of toxic baits to eradicate or control rats, mice, and mongoose from future translocation sites might also be controversial in some communities.
2. Control of feral mallards (*Anas platyrhynchos*), which might hybridize with LADU, could be controversial in some communities. Hybridization could destroy the genetic identity of the LADU, so control of feral ducks may be required on some of the MHI.

Ecological context

The Hawaiian archipelago is the world's most isolated group of islands, lying approximately 4200 km from the nearest continental land mass and featuring extremely high rates of biotic endemism. About two-thirds of endemic bird species have been extirpated since human colonization around 400 A.D., and half of the birds present at the time of the first recorded European contact (1778) have disappeared within the last two and one-quarter centuries. Since the arrival of rats to the MHI about 1000 years ago, the LADU occurred only on Laysan Island and Lisianski Island (about 250 km northwest of Laysan). LADU were extirpated from Lisianski in the mid-1800s after successive shipwrecks with hungry shipwrecked mariners and the introduction of mice, which denuded the island's vegetation (Olson and Ziegler 1995). Subfossil and ancient DNA evidence indicates the occurrence of LADU throughout the archipelago; to date, their bones have been found on the islands of Hawai`i, Maui, Moloka`i, O`ahu, Kaua`i and Lisianski (Olson and James 1991; Olson and Ziegler 1995; Cooper *et al*. 1996). The extirpation of the LADU from the MHI likely resulted from predation by Polynesian rats (*Rattus exulans*), the probable cause of the decline and extinction of many other native Hawaiian birds (James and Olson 1991; Burney *et al.* 2001).

One of three extant and at least ten extinct Anseriformes endemic to Hawai`i (Olson and James 1991; Helen James, pers. comm.), the LADU has the most restricted range of any duck in the world. The naturally occurring population is estimated to be 581 adult birds (95% CI 503–682; Reynolds and Citta 2007) on Laysan Island (415 ha, 12 m maximum elevation). The reintroduced population, established via wild translocations of 42 individuals during 2004 and 2005 (Reynolds *et al*. 2008) has been estimated to be 375 adult birds (U.S. Geological Survey data) on Midway Atoll (592 ha, 5 m maximum elevation, 620 km northwest of Laysan). These small population sizes might compound the risk of associated with low genetic variability and vulnerability to new diseases after historic population bottlenecks and founder effects during translocations.

Both Laysan Island and Midway Atoll are characterized by high daytime temperatures in the summer, frequent intense storms, high evaporation rates, and, on Laysan, limited supplies of fresh water. The ducks are also at risk from outbreaks of disease such as botulism (type C), *Echinuria* nematodes (Work *et al*. 2004, 2010), and possibly avian malaria, avian influenza, avian cholera, duck plague, and West Nile virus. At present, Laysan Island and Midway Atoll provide some insurance from diseases since both islands are unlikely to experience catastrophic epizootics (i.e., disease outbreaks) simultaneously. Likewise the possibility of accidental introductions of mammalian predators presents an ongoing risk of extinction for the LADU. In addition, the low mean elevation of the NWHI puts LADU populations at risk from predicted increases in mean sea level and from increased frequency and intensity of storms (and their associated effects such as high storm surges).

Decision Structure

Objectives and Constraints

We identified a set of objectives including:

1. Maximize persistence probability of LADU. Measurement criterion: Probability of species persistence as measured by an appropriate population viability analysis. Measurement target: At least 99% probability of persistence for 100 years.
    a. Maximize the extent of LADU range. Measurement criterion: number of islands & hectares.
    b. Maximize the elevation and diversity of LADU range. Measurement criterion: elevations of islands inhabited & type of habitat occupied.
    c. Minimize the chance for inbreeding depression in small, isolated and newly established populations. Measurement criterion: maintain existing genetic diversity (allele frequencies and heterozygosity).
    d. Minimize favorable conditions for epizootics. Measurement criteria: wetland water temperatures for botulism, vaccination of birds, ability to remove carcasses.
    e. Minimize the chance of introducing exotic predators to existing or potential LADU range. Measurement criterion: number of exotic predator introductions.
2. Minimize management costs. Measurement criterion: dollars.

3. Minimize the chance of hybridization between LADU and other duck species (e.g., feral mallards). Measurement criterion: number of inter-specific matings expected to involve LADU.
4. Minimize conflicts and disturbance of other native species. Measurement criterion: number of expected reductions in abundance of other native species due to management actions taken for LADU (i.e. wetland restoration near seabird colonies).
5. Minimize the chance of introducing exotic taxa to islands as a result of LADU management actions. Measurement criterion: expected number of exotic species introduced to islands as a result of LADU management actions.
6. Minimize social and political conflict. Measurement criterion: stakeholder satisfaction.

We focused primarily on objective 1 in our prototype model. A cost model, relevant to objective 2, will be built with island-specific considerations (see *Alternative Actions* for integration of predator eradication and habitat management actions into the cost model). Important uncertainties influence objective 3, in that it is currently unknown whether hybridization and introgression with feral ducks will occur in the wild; however, we did incorporate probability of hybridization events in our initial prototype models (see below, Figures 3 & 5). Objective 4 was not explicitly considered and will require additional development as the LADU-specific model is scaled up to multiple species of various island ecosystems. Objective 5 will primarily be integrated through constraints on the set of actions considered and incorporated in island-specific translocation plans and techniques rather than through management strategies (e.g., limiting movements of individuals from "non-pristine" to "pristine" islands, implementing best management practices such as quarantine and freezing of equipment, cleaning ducks' feet and feathers, parasite treatments etc., prior to translocating individuals). Finally, objective 6 is expected to be affected primarily by non-native predator control and eradication actions such as toxicant baits on the MHI. Our rapid prototype did not fully address this objective because we bounded our decision problem exclusively to islands lacking human habitation (see below). We did discuss public education efforts to help ameliorate concerns about non-native predator management, particularly on uninhabited islands.

Management actions

We identified an initial comprehensive list of management actions, including:

1. Translocation of LADU from wild populations to unoccupied islands.
2. Habitat management.
    a. Creation or restoration of freshwater wetlands.
    b. Protect or create dense vegetative cover to provide nesting, resting, and foraging habitat. Management of vegetation may include restoration of native vegetation. Eradication of undesirable (invasive) vegetation should be attempted prior to endangered species translocations (since LADU may nest, forage, and seek cover in "weeds").
    c. Ecosystem management to increase prey availability (primarily arthropods, but also certain aquatic grasses) for LADU.

3. Exotic predator eradication from islands, specifically eradication of rats, feral cats, feral dogs, and mongoose (and also pigs, for scenarios involving translocation sites within the main Hawaiian Islands).
4. Mosquito control to reduce disease risks to LADU and other native birds.
5. Control of feral mallards to reduce risk of hybridization with LADU.
6. Captive rearing and release including establishment of captive breeding programs managed specifically for re-introduction of LADU to unoccupied islands after threats are reduced.
7. Habitat engineering, such as building seawalls or artificial accretion (or fill) to protect islands from impacts of sea level rise.
8. Exotic predator control, including protecting areas with predator-proof barriers and reducing the abundance of predators within the protected area.
9. Disease management, including vaccination against particular diseases and management of disease outbreaks.

Our model included only actions 1 and 6, but assumed that actions 2–5 would have already taken place on islands where necessary before translocations were attempted. This assumption was made because, given the rarity and highly endangered status of LADU, translocations would only occur where there was a high chance of persistence, and without the appropriate habitat improvements beforehand, extirpation (reintroduction failure) would be highly likely. Additionally, the costs of those actions would be incorporated into the costs of translocation (however, the model also allows for uncertainty as to when predator eradication would take place). Action 7 was included implicitly in the one island model for which it was most appropriate, Midway Atoll, through a modification to the function relating sea level to island size. Predator control (action 8) was not considered explicitly but will ultimately be integrated into island-specific models as appropriate. Finally, disease management was also not included explicitly as an action, though it was assumed that any available technologies for managing disease would be adopted to reduce extinction risks.

Another aspect of the comprehensive list of actions is the spatial scope of the management plan, i.e., which islands are under consideration for the management of LADU. We identified the following islands as prime candidates for LADU management:

1. Laysan Island, NWHI: currently occupied, 12 m maximum elevation, 415 ha, no mammalian predators.
2. Midway Atoll, NWHI: currently occupied, 5 m maximum elevation, 592 ha, no mammalian predators.
3. Lisianski Island, NWHI: currently unoccupied, 11 m maximum elevation, 150 ha, no mammalian predators.
4. Nihoa Island, NWHI: currently unoccupied, 269 m maximum elevation, 68 ha, no mammalian predators.
5. Kurie Atoll, NWHI: currently unoccupied, 6 m maximum elevation, 100 ha, no mammalian predator threats.
6. Kaho`olawe, MHI: currently unoccupied, 450 m maximum elevation, 12,100 ha, rats and cats currently present.

We excluded the remainder of the MHI from consideration in our rapid prototype to keep the problem bounded and manageable. Though one day in the future some sites in the MHI may be deemed suitable, at this time, predator issues present nearly insurmountable challenges. All of the prime islands listed here, with the exception of Midway Atoll, are uninhabited or are inhabited only by USFWS or state managers or researchers. Introductions to inhabited islands in the MHI will involve much greater complications in terms of stakeholder acceptance given the need for predator eradication and/or control. Additional islands in the MHI that could eventually be considered include Ni`ihau and Lanai, if rats, feral cats, dogs, and feral mallards could be effectively controlled.

Predictive model

We built an initial prototype in the form of a spatially-implicit occupancy model, allowing users to modify input parameters and examine the relative utility of alternative management actions. The primary function of this model was to demonstrate how a more spatially-explicit and detailed stochastic occupancy model would function. We created a utility function to reflect the fundamental objectives of maximizing LADU persistence while accounting for costs. Model output is a utility value on the interval (0-1) that is equal to zero if a cumulative budget is exceeded or is equal to the probability of persistence for 100 years if the budget is not exceeded. This probability of persistence is a function of the number of islands of two types (low islands and high islands) occupied at year 100 and their respective, island height-specific persistence probabilities. As such, the utility (*U*) function is:

$$U = \begin{cases} 1 - (E_{low,100})^n (E_{high})^m & if\ C \leq B \\ 0 & if\ C > B \end{cases}$$

where $E_{low,100}$ = probability of extinction in year 100 (this probability varies with year) on each of *n* low islands occupied in year 100, E_{high} = probability of annual extinction on each of *m* high islands occupied in year 100 (this probability is constant across years), *C* = realized cost, and *B* = budget. The model requires the following parameters as input: 1) number of low-elevation islands, 2) number of high-elevation islands, 3) initial number of islands occupied in each elevation category, 4) annual probability of extinction on a high island, 5) intercept and slope describing the increasing probability of extinction on low islands due to sea level rise over time, 6) cost of translocating to a low island, 7) cost of translocating to a high island, 8) cost of annual monitoring on occupied islands (though we recognize that monitoring is not necessary in this model, i.e., the model is not formally adaptive), and 9) budget. For demonstration, we assume there are four low islands, two of which are occupied initially, and two high islands that are not occupied initially. We can use the following model to describe the relationship between probability of extinction on a low island and year (*y*):

$$logit(E_{low,y}) = \beta_0 + \beta_1 year$$

and assume that β_0 = -4.7 and β_1= 0.2 to represent a relatively pessimistic scenario for sea level rise (Figure 1).

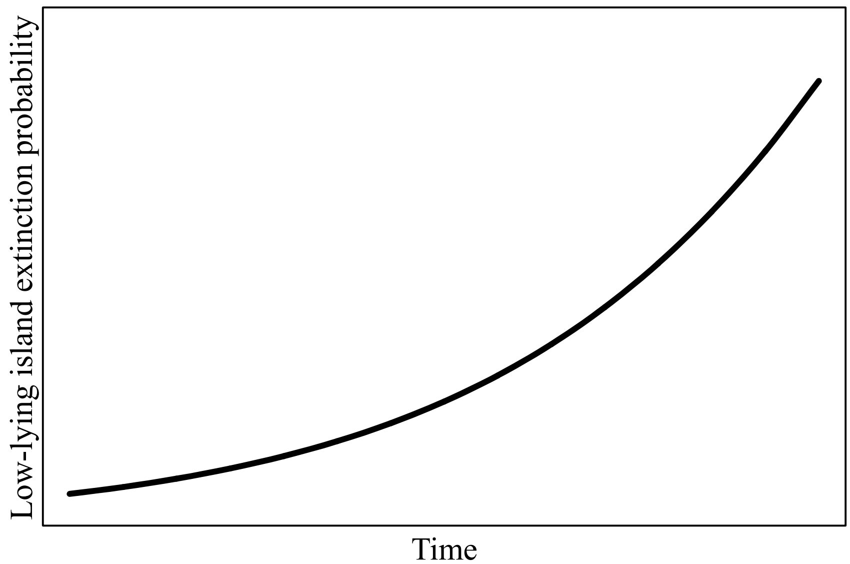


Figure 1: Hypothetical time-dependent extinction probability related to sea-level rise for the four low-lying islands in the Papahanaumokuakea Marine National Monument, first prototype model.

In this model, islands unoccupied by LADU remain unoccupied until a translocation, as we assume that LADU will not colonize other islands on their own. For occupied islands, occupancy state in the following year is based on an independent Bernoulli trial with probability $E_{low,y}$ for low islands and probability E_{high} for high islands. We assume E_{high} = 0.1. If an island is unoccupied, then LADU may be translocated to that island that year, changing island status to occupied. Thus, the model tracks occupancy through time, and the utility is based on the probability of persistence at the end of the time period. The simplicity of this model poses problems and limitations. For example, lumping islands into low and high elevation categories ignores the likely unique effects of sea-level rise on each of the small islands. For example, the utility function budgetary threshold places extreme restrictions on the management strategy; does any given strategy really have no utility if it exceeds the stated budget by one dollar? With this prototype as our starting point we proceeded to develop a more complex, biologically and management-relevant model.

After developing the initial prototype, we greatly expanded the model complexity by developing an influence diagram that expressed all the ecological and environmental factors that we thought would affect LADU abundance and persistence on any given island in the Hawaiian archipelago (Figure 2; at end of document). We described how factors such as mammalian predator introductions or disease epizootic outbreaks would affect LADU populations. We also included the possible effects of global climate change and especially sea level rise on LADU population dynamics. The influence diagram depicts implementation of management actions and how those actions might affect the system.

We also developed a schematic to link the islands in the archipelago together (Figure 3; at end of document). That schematic depicts the links between populations on different islands and represents the probable presence of spatial autocorrelation of catastrophic events (hurricanes, tsunamis, etc.) across the 2000 km long archipelago. It also depicts management actions involving translocations of ducks among islands from captive or wild sources of birds. We envision a nested modeling approach where we model each island (Figures 2 & 3), and those island specific models are nested in a regional model that links the island (and captive source) models together through translocations and spatial autocorrelation.

Once we developed the detailed, island-specific influence diagram (Figure 2) we worked to reduce it to a more tractable and useful model. The detailed influence diagram contains more specifics than appears necessary to inform decision-making. Using the detailed influence diagram as a starting point, we focused in on the key relationships and the key uncertainties in the system which may affect decision-making. We identified mammalian predators, disease, catastrophes, and habitat availability as the primary drivers of LADU population dynamics (Figure 4; at end of document). Sea-level rise due to climate change is expected to affect duck populations indirectly through habitat availability (i.e., sea-level rise causes habitat inundation) and catastrophes (i.e., climate change induced changes in storm frequency and intensity, changes in El Niño frequency).

For determining optimal management activities, we envision a quantitative version of this model (Figure 4). The model consists of a set of island-specific multi-occupancy states, where each island would be (0) unoccupied, (1) occupied but with low abundance (< 100 individuals), (2) occupied with moderate abundance (100 to 300 individuals), or (3) occupied with high abundance (> 300 individuals). Alternatively, the state definitions could be simplified to include (0) unoccupied, (1) occupied but unsuitable for translocation extraction, or (2) occupied and suitable for translocation extraction. Suitability for translocation extraction would be related to island population size and extinction risk to that population; if a small population persists on an island with very high inundation probability (e.g., Kure atoll) extracting individuals for translocation might be suitable despite the small population size and elevated probability of extinction due to the extraction.

For the purposes of this rapid prototype workshop, we used the abundance-based four state occupancy model described above. Transition from one state to another would then be modeled as a binomial process with stochastically-varying annual mean transition rates. These island-specific models would be linked through translocation actions and movements in and out of a captive population, and these models would also be related through spatial autocorrelation in stochastic effects (Figure 3). We envision development of baseline island-specific state transition probabilities to reflect island carrying capacities and differing threats on each island (Table 1). For example, Midway Atoll with its greater freshwater availability, larger size and densely vegetative areas, would have much higher transition rates to state 2 and 3 than would Lisianski Island which is smaller, more sparsely vegetated and contains less freshwater. For the above reasons Midway would also be expected to support more ducks.

Table 1. Partial list of hypothesized baseline mean annual transition probabilities between occupancy states for Laysan ducks in the Hawaiian archipelago.

	Island					
Transition[a]	Laysan	Midway	Lisianski	Nihoa	Kure	Kaho'olawe
1 to 2	0.2	0.5	0.2	0.1	0.1	0.5
2 to 3	0.3	0.3	0.05	0	0	0.3
3 to 2	0.05	0.3	0.9	0	0	0.3
2 to 1	0.05	0.05	0.15	0.7	0.7	0.05
1 to 0 old[b]	0.1	0.1	0.1	0.1	0.1	0.1
1 to 0 new[b]	0.3	0.3	0.3	0.3	0.3	0.3
2 to 0	0.01	0.01	0.01	0.01	0.01	0.01
Other transitions	0	0	0	0	0	0

[a] States include: 0) unoccupied, 1) occupied but with low abundance (< 100 individuals), 2) occupied with moderate abundance (100 to 300 individuals), and 3) occupied high abundance (> 300 individuals).

[b] Transition probability for a newly translocated population differs from that for a population established > 1 year ago.

We also envision incorporating island-specific time-dependent extinction probabilities (i.e., transitions to state 0) and other downward transition probabilities based on the expected effects of sea-level rise (Figure 5). A model describing the changes in extinction probabilities over time would take the general form:

$$logit(E_{low}) = \beta_0 + \beta_1 year$$

where β_0 and β_1 would be specified for each island based on area, elevation, and availability of habitat (e.g., freshwater sources). The intercepts (β_0) would be informed by the baseline state transition probabilities given in Table 1, which are independent of sea level rise. The slope parameters (β_1) would reflect island topography and the expected loss of carrying capacity as a function of rising sea level. Given the tremendous uncertainty in sea level rise and the influence that sea level rise is expected to have on the optimal sequence of translocation actions, we envision development of competing models of sea level rise (i.e., differing β_1 values for each island under different models of sea level rise effects).

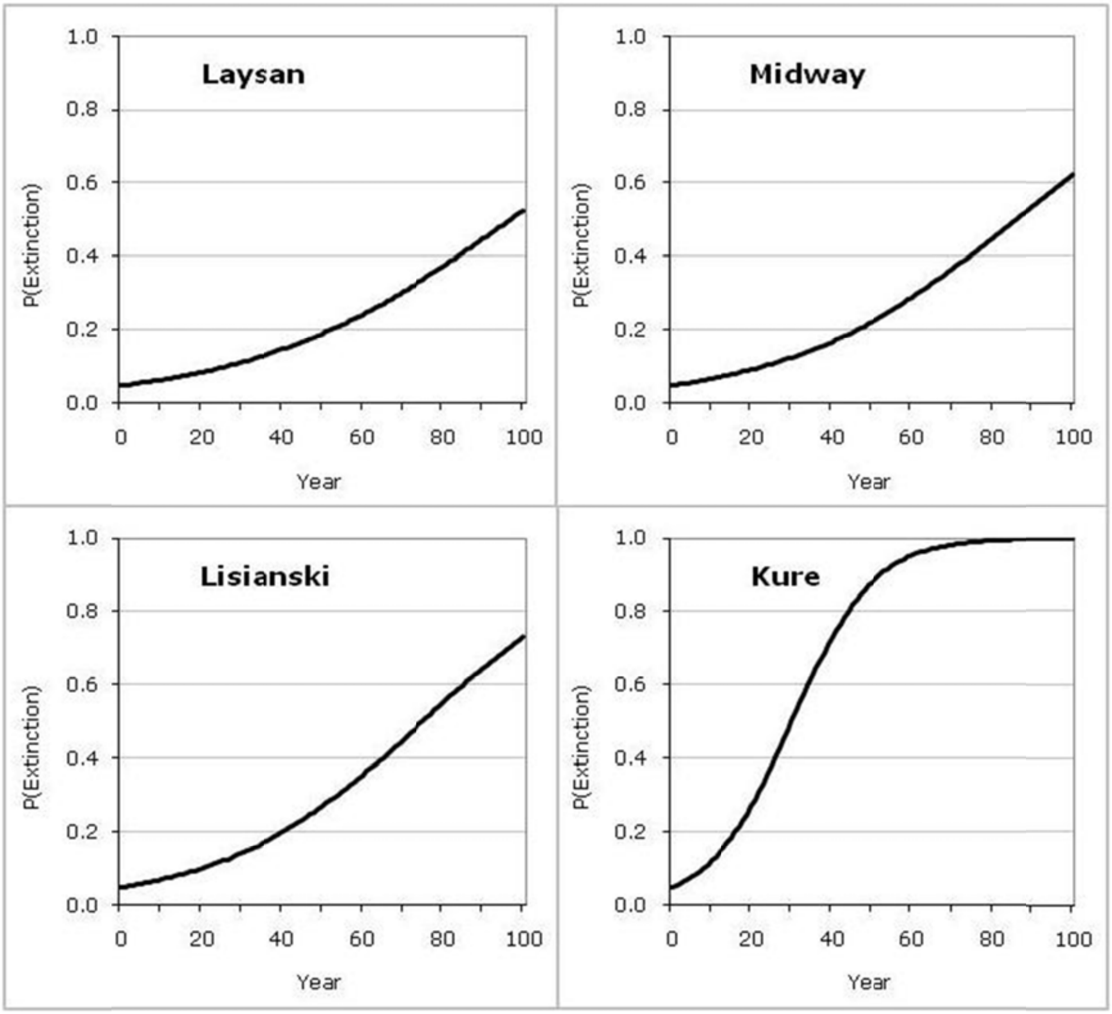


Figure 5: Hypothetical island-specific functions describing the change in extinction risk over time due to a hypothetical sea level rise. Island-specific extinction probabilities will be based on island area, elevation, habitat availability and the potential impact of sea level rise, as determined from Digital Elevational Models (DEM), satellite imagery, and vegetation maps.

Catastrophes, new disease, and predator introductions will be modeled as random binary occurrences with low, island-specific annual probabilities (< 0.1). The model would include island-specific probability distributions for occurrence of catastrophes, disease, and predator introductions. For example, Midway Atoll, with an airport and relatively frequent boat traffic, will likely have higher probabilities of accidental mammalian predator introduction than will Laysan Island, which is infrequently visited. Once predators arrive on an island, the downward state transition probabilities (i.e., 2 → 1, 1 → 0) will increase until predators are eliminated. We also envision inclusion of spatial autocorrelation in catastrophe occurrence, i.e., annual probabilities of catastrophe will be positively correlated and the strength of the correlation will be inversely related to distance between islands. For example, since Kure Atoll and Midway

Atoll are only 90 km apart, if a tsunami or a hurricane hits one of these islands, it is likely to hit the other as well. Modeling catastrophes, disease, predator introductions, and island-specific characteristics using state transitions will allow us to develop a state-dependent decision strategy that incorporates a variety of environmental uncertainty.

Decision Analysis

A stochastic optimization method is needed for identification of optimal actions under the quantitative version of the model represented in Figure 4. In the initial demonstration model, we used the numerical optimization tool available in Microsoft Excel to generate the optimal set of actions using a 15-yr rather than a 100-yr time horizon, to overcome optimization problems. The optimization was constrained by annual budget limitations. Actions were restricted to one translocation per year, and the solver algorithm had to determine whether to translocate to a high island, a low island or do nothing in each of the 15 years. Even with this simple model, the optimization tool available in MS-Excel had difficulty finding optimal, or even admissible, solutions. Admissible solutions that were identified generally involved two to three translocations among the four modeled low-lying islands within the first few years and recommended a single translocation to one of the two high-lying islands in year 14 or 15 of the decision sequence. The results—two consecutive translocations during the last two years of the sequence—highlight the limitations of setting a short-term decision timeline and optimizing on a single probability value at the end of that decision time frame rather than using a time independent, state-dependent optimization approach.

An optimal decision analysis using the multi-state model described in Figure 4 and above presents, to our knowledge, a novel optimization problem for natural resources management. To our knowledge, available optimization software requires that dynamic models use first-order Markovian processes (i.e., a time-varying random phenomenon without memory where the present is independent of the past), yet climate change-induced shifts in state dynamics are by nature non-Markovian and therefore present great challenges for optimization. We anticipate that the decision analysis used to evaluate management options for LADU in the NWHI will require some complex computer programming. Otherwise, a less intensive decision analysis using simulation-based approaches could be applied, with varying sequences of management actions. All things considered in this case study, it may be acceptable to identify a quasi-optimal set of management actions that still achieve objectives: acceptable levels of persistence probability for LADU while staying within budgetary constraints, and maintaining the genetic identity of the species and public support.

Uncertainty

There are several important sources of uncertainty, identified in our simplified influence diagram (Figure 4), relevant to the modeling of long-term LADU persistence. It is useful to classify these as structural or epistemic uncertainty (uncertainty in our knowledge of system function, which can be reduced over time with system monitoring) and aleatory uncertainty (practically irreducible variation in system function over space and time).

Epistemic Uncertainty

In Figure 4, we identify four crucial sources of epistemic uncertainty. First, of greatest interest is the substantial uncertainty related to the impact of climate change on this system. This is manifested through at least three forms of uncertainty: 1) magnitude and rate of future sea level rise, 2) whether and at what rate storm events will increase over time, and 3) whether intensity of storm events will become more severe with sea level and global temperature rise. We imagine that climate change related uncertainty will be modeled explicitly using multiple models of climate change, sea level rise, and other associated impacts. Clearly, models of sea level rise are a major area of development in the larger scientific community, and presumably over time the uncertainty in the magnitude of sea level rise will be reduced; such information can be integrated into the LADU management framework by updating degrees of belief in different predictions of sea level rise.

A second source of uncertainty is the expected time required to eradicate predators. We imagine entertaining competing models of predator eradication rate (e.g., a “best case” model and a “worst case” model). Monitoring data may become available over time (if predator eradication is attempted over larger islands in the MHI in the coming years) with which to update belief in these competing models. To date the largest island rat eradication in Hawai`i was on Midway Atoll, 592 ha; that project required a sustained three-year, million-dollar effort, but methods have been refined and further improvements can be achieved iteratively within annual adaptive management cycles. Recent rat eradictions over much larger areas, such as New Zealand's Campbell Island (11,300 ha, almost the same size as Kaho`olawe), have been accomplished within two years.

Third is the risk of highly pathogenic diseases for isolated island species. Translocations to the MHI will almost certainly bring LADU in contact with disease vectors and new disease risks. There is uncertainty about whether LADU are susceptible to the several mosquito-borne diseases found in the MHI. This uncertainty may also be captured through multiple models, though we anticipate that additional information may come from captive populations before extensive reintroductions on the MHI take place. Some information about LADU disease susceptibility may already be available from the few LADU living in zoo populations around the world and their current co-existence with *Ades* mosquitoes and pox virus on Midway Atoll.

Fourth is whether or not LADU will hybridize in the wild. However, based on a precautionary principle, managers will avoid translocations to areas where there is significant risk of hybridization with other resident duck species. In the context of our workshop we applied this uncertainty as a tactical and management action constraint. We did not allow the use of sites with current endangered Koloa or feral Mallard populations to be considered as translocation sites in order to protect and maintain the genetic identity of both endangered waterfowl species.

Additional sources of structural uncertainty will be identified during development of a quantitative population model. For example, the amount of prey available to support LADU on each island, and, related to this, the carrying capacity on each island under consideration will be uncertain. Estimation of carrying capacity will be an important part of the development of quantitative models; ultimately, these models may be developed using data available from

Laysan and Midway, and uncertainty about parameter values can be formally integrated into modeling by allowing these parameters to vary over model simulations. We anticipate such an approach will be taken for several parameters in the quantitative model, especially in cases where expert opinions of parameter values vary substantially.

Aleatory Uncertainty

We expect to use stochastic process models to account for the probability of disease introduction, predator introduction, weather catastrophes, and reintroduction success. We also anticipate modeling island-specific variation in habitat quality when building models of carrying capacity.

The effect of demographic stochasticity on whether an established island population becomes locally extinct in a given year, given a probability of extinction, will be modeled using Monte Carlo simulation methods standard in population modeling.

Discussion

Prototyping process

The team engaged in significant work in advance of the workshop, including three conference calls with the leadership team (the team coordinator and SDM coaches) and two phone calls with the full team. The team leadership drafted a problem statement and then presented the problem statement to the full team for discussion during the conference calls. With that advance work, the team was able to proceed directly to management objectives and action alternatives on the first day of the workshop. We identified objectives using relevant recovery criteria from the LADU Recovery Plan (USFWS 2009) as a guide, and discussed risk tolerance for LADU extinction.

We brainstormed a potential list of actions that could go into the prototype and used these objectives to develop the first relatively simplistic prototype for evaluating actions and consequences. In the initial stages of adding complexity to the predictive model, it became apparent that our time would be better spent describing a full model rather than programming a second prototype. Thus, the group agreed to set forth on developing a more comprehensive conceptual model, remaining as realistically inclusive as possible. Once the larger model was developed, we discussed the uncertainty, variability, structure, tools, and data available for each of the model component relationships. The next step was to identify components particularly important to a less complex model for decision-making in the face of sea level rise. Working on the problem statement and getting the whole team in agreement on a problem statement in advance of the workshop week was hugely beneficial to our progress through the rapid prototyping process.

<u>“Mud bog”</u>: There were a few times when we got bogged down on the best way to model an action or other details. However, the team leaders, who also served as facilitators, kept us from getting stuck in the mud for too long. For example, we couldn’t come to an agreement on how to model accidental introductions of plants and animals, thus, we set it aside to get more information and discuss at a later time so we could move on. Early on, a key decision-maker on the team was able to give the team guidance on what information is and is not needed to make decisions on when, how, and where to spend limited conservation dollars, which was critical in

keeping the team focused and working toward the ultimate objective: maximizing the probability of species persistence given sea level rise, the limited number of islands available for translocation, and the challenge of restoring islands to conditions suitable for translocation. Roles: Of nine people (some with multiple roles), our team consisted of one species expert, one expert on another endangered NWHI bird species, one expert on other endangered Hawaiian waterbirds, one generalist expert in Hawaiian species, six quantitative ecologists, one avian ecologist, and one major decision maker. We found that it was extremely beneficial to have a decision maker on the team, especially when it came to identifying ways to simplify the model. The decision maker easily looked at our increasingly complex influence diagram and could say 'I don't need to know about this issue and its effect on LADU to make this decision.' Participation of a decision maker in the rapid prototyping helped prevent getting bogged down in system details that are unimportant for decision-making. At one point this member boiled down the problem to "Do we need the island of Kahoolawe (to prevent these extinctions) and if so, when do we need it?"

Next Steps

In addition to endangered terrestrial species, the NWHI also provides habitat for the largest (~14 million birds of 22 species) and most important assemblages of tropical seabirds in the world. Development of this case study will contribute to the future development of adaptation plans for seabird populations as well. Insurance populations can also be established for these species on higher islands, primarily through natural colonization (and appropriate preparation of candidate sites through habitat restoration, exotic predator exclusion fences or small island eradications, and social attraction techniques such as vocalizations and decoys) or, perhaps, through assisted colonization techniques for procellarid chicks. The preparation of some candidate sites will require tremendous initial effort and consistent of long-term monitoring to ensure the continued suitability of sites as well as population health. This work will entail tremendous effort, expense, and risk high probability of failure given limited budgets or lack of political will. We would like to use additional Pacific Sea Level Rise case studies (i.e., Laysan Finch, Black-footed Albatross, LADU phase 2, and one TBD topic) in a SDM workshop based in Hawai`i, so that Papahanaumokuakea managers can participate in developing these decision tools. This U.S. Geological Survey/Fish and Wildlife Service (FWS) sponsored workshop could be preceded by a SDM class and would ideally occur in Feb 2011 with state and FWS managers and biologists.

Recommendations

We recommend continuing to utilize the tools of structured decision-making to guide further model development, endangered species management, research, and monitoring in the NWHI. The basic framework that we have developed herein could be easily transferred to a number of species that face similar threats in the Papahanaumokuakea Marine National Monument. The tools will help create a more efficient system for management decision-making and research activities, an important consideration for research in these extremely remote field sites. A structured approach may allow managers to evaluate the potential trade-offs between short-term gains in population numbers with the longer-term probability of species persistence in the face of sea level rise. The predictive modeling and the decision analysis that we have described in this report will require substantial effort and some creative thinking in the months and years following this workshop. A state- and time-dependent optimization or quasi-optimization analysis, in particular, will likely require substantial software development and some creative approaches.

Literature Cited

Burney, D. A., H. F. James, L. P. Burney, S. L. Olson, W. Kikuchi, W. L. Wagner, M. Burney, D. McCloskey, D. Kikuchi, F. Grady, R. I. Gage, and R. Nishek. 2001. Holocene lake sediments in the Maha`ulepu caves of Kaua`i: evidence for a diverse biotic assemblage from the Hawaiian lowlands and its transformation since human arrival. *Ecological Monographs* **71**:615–642.

Cooper, A., J. Rhymer, H. F. James, S. L. Olson, C. E. McIntosh, M. D. Sorenson, and R. C. Fleischer. 1996. Ancient DNA and island endemics. *Nature* **381**:484.

James, H. F., and S. L. Olson. 1991. Descriptions of thirty-two new species of birds from the Hawaiian Islands: Part II, Passeriformes. *Ornithological Monographs* **45**:1–88.

Olson, S. L., and A. C. Ziegler. 1995. Remains of land birds from Lisianski Island, with observations on the terrestrial avifauna of the Northwestern Hawaiian Islands. *Pacific Science* **49**:111–125.

Olson, S. L., and H. F. James. 1991. Descriptions of thirty-two new species of birds from the Hawaiian Islands: Part I, non Passeriformes. *Ornithological Monographs* **46**:1–88.

Reynolds, M. H., and J. J. Citta. 2007. Post-fledging survival of Laysan Ducks. *Journal of Wildlife Management* **71**:383–388.

Reynolds, M. H., N. E. Seavy, M. S. Vekasy, J. L. Klavitter, and L. P. Laniawe. 2008. Translocation and early post-release demography of endangered Laysan teal. *Animal Conservation* **11**:(2)160–168.

USFWS. 1967. Laysan duck *Anas laysanensis*. *Federal Register* **32**(48):4001.

USFWS. 2009. Revised Laysan duck recovery plan. U.S. Fish and Wildlife Service, Portland, OR.

Work, T. M., J. L. Klavitter, M. H. Reynolds, and D. Blehert. 2010. Avian botulism: A case study in translocated endangered Laysan Ducks (*Anas laysanensis*) on Midway Atoll. *Journal of Wildlife Diseases* **46**(2):499–506.

Work, T. M., C. U. Meteyer, and R. A. Cole. 2004. Mortality in Laysan Ducks (*Anas laysanensis*) by emaciation complicated by *Echinuria uncinata* on Laysan Island, Hawaii, 1993. *Journal of Wildlife Diseases* **40**(1):110–114.

List of Figures

the diagram, objectives are contained in oval nodes, ecological/environmental factors are contained in rectangles, and management actions are contained in hexagons.

Figure 3 (Page 19): Model schematic depicting the links between Laysan Duck populations on different islands in the Hawaiian archipelago. Islands in close proximity have spatially correlated catastrophe probabilities (hurricanes, tsunamis) and the links between islands represent translocation actions.

Figure 4 (Page 20): A model schematic for the ecological and environmental factors that affect Laysan Duck populations on any given island in the Hawaiian archipelago. This model identifies the key uncertainties expressed in the more complicated influence diagram (Figure 2) and simplifies the influence diagram by combining links and nodes of stochastic variation into other model parameters. In the diagram, objectives are contained in oval nodes, ecological/environmental factors are contained in rectangles, and management actions are contained in hexagons.

Figure 5 (Page 11): Hypothetical island-specific functions describing the change in extinction risk over time due to a hypothetical sea level rise. Island-specific extinction probabilities will be based on island area, elevation, habitat availability and the potential impact of sea level rise, as determined from Digital Elevational Models (DEM), satellite imagery, and vegetation maps.

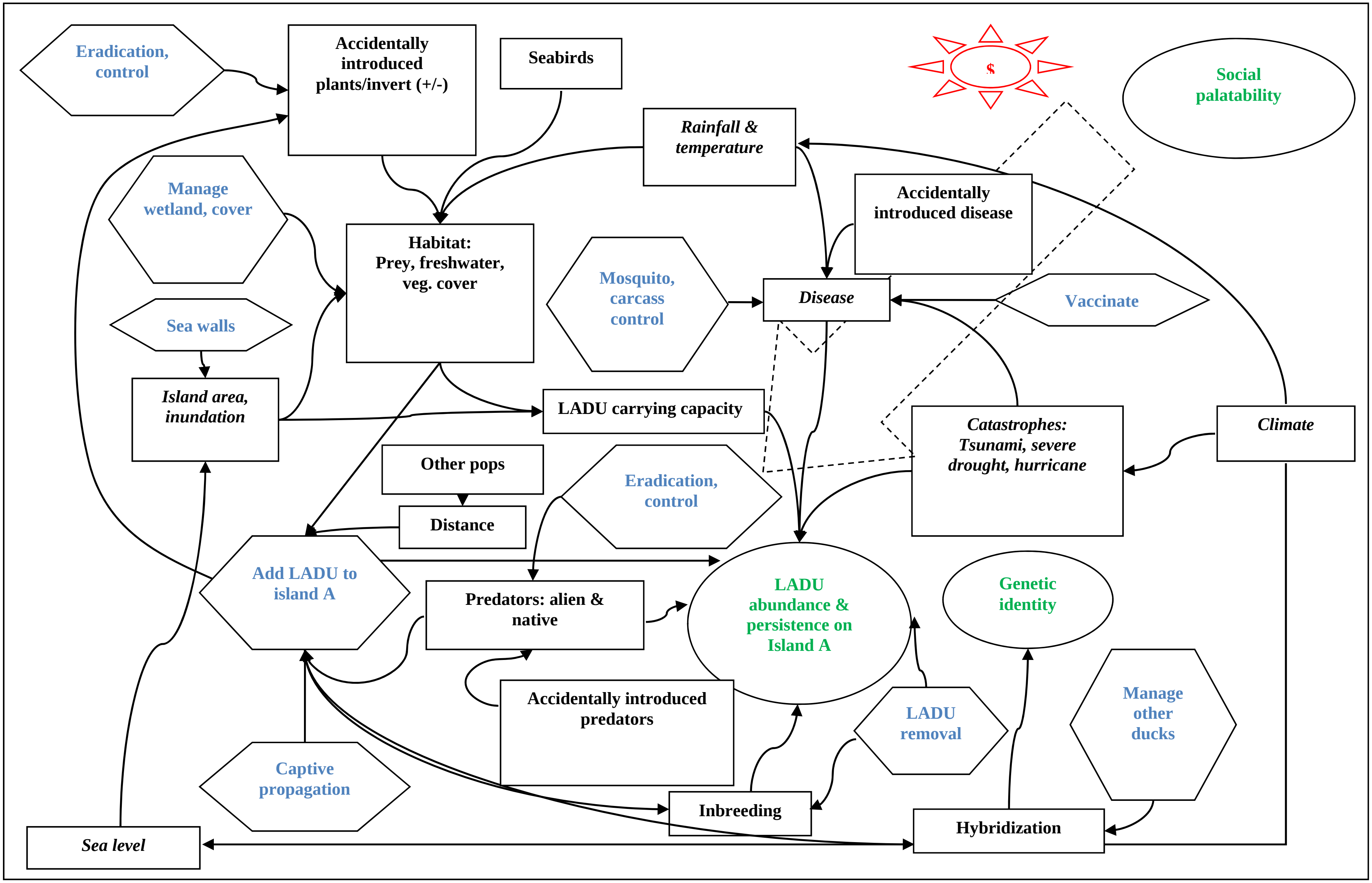

Eradication, control
Accidentally introduced plants/invert (+/-)
Seabirds
$
Social palatability
Rainfall & temperature
Manage wetland, cover
Accidentally introduced disease
Habitat: Prey, freshwater, veg. cover
Mosquito, carcass control
Disease
Vaccinate
Sea walls
Island area, inundation
LADU carrying capacity
Catastrophes: Tsunami, severe drought, hurricane
Climate
Other pops
Eradication, control
Distance
Add LADU to island A
Predators: alien & native
LADU abundance & persistence on Island A
Genetic identity
Accidentally introduced predators
LADU removal
Manage other ducks
Captive propagation
Inbreeding
Hybridization
Sea level

Figure 2.

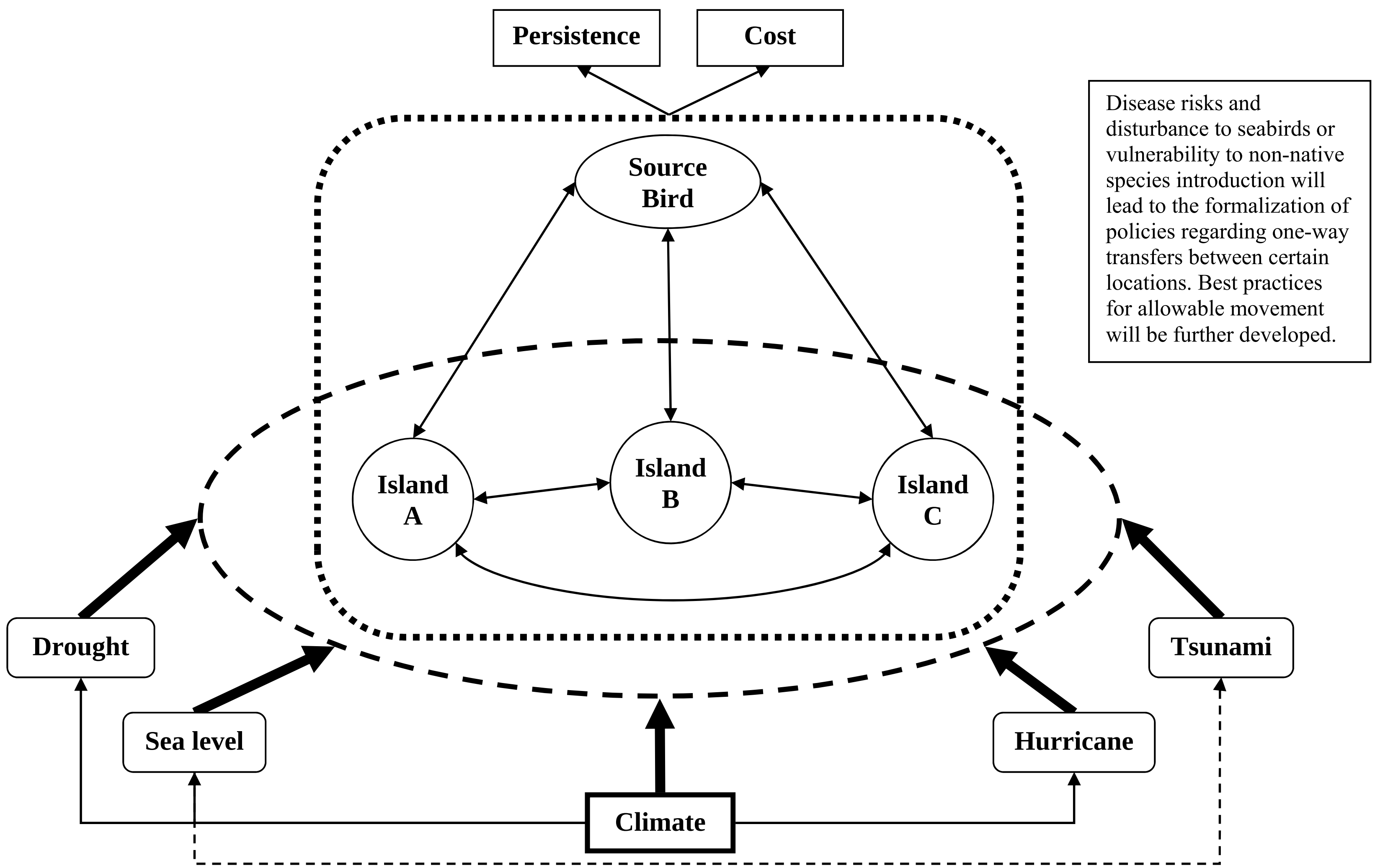
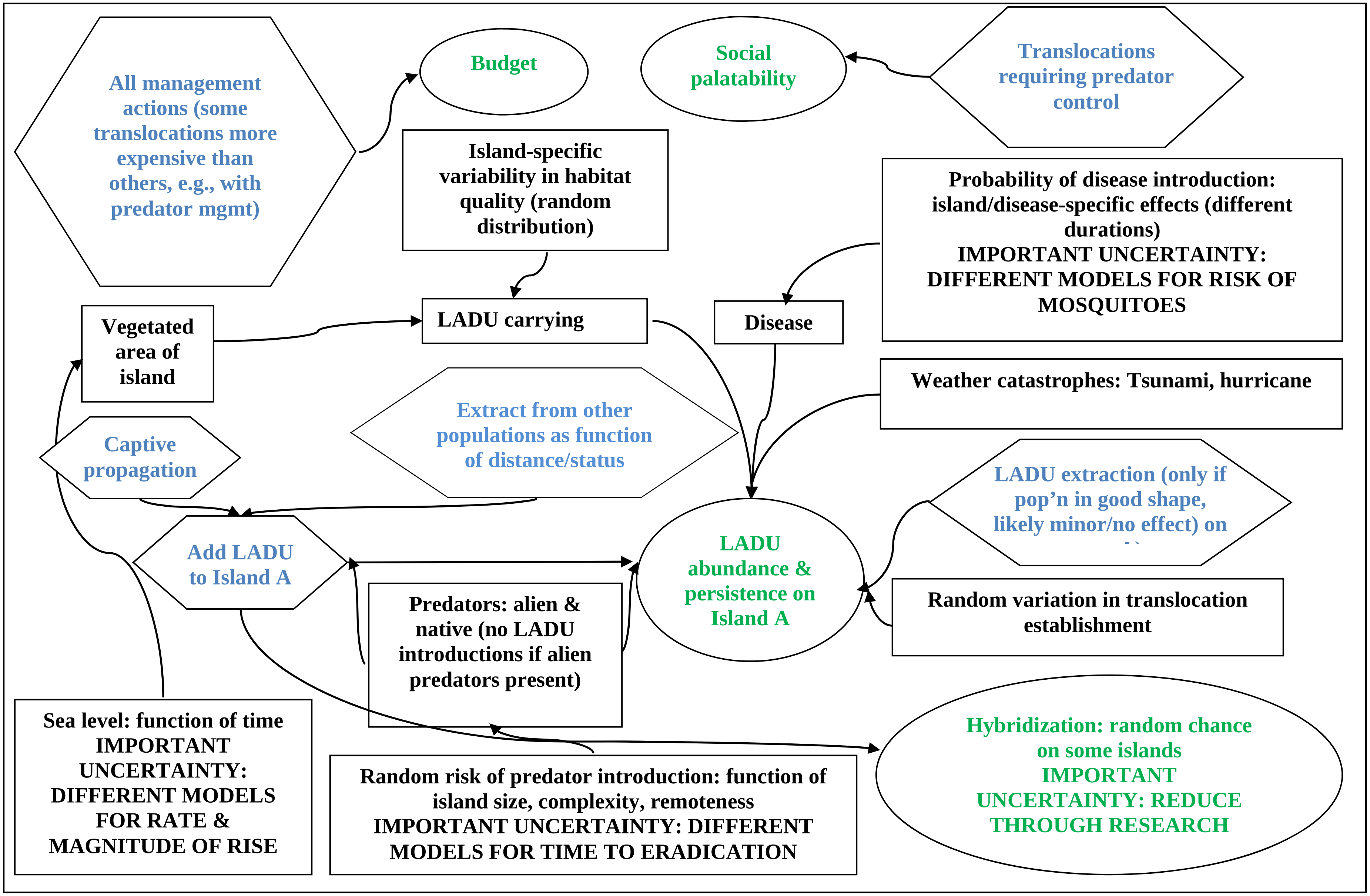

Persistence
Cost
Disease risks and disturbance to seabirds or vulnerability to non-native species introduction will lead to the formalization of policies regarding one-way transfers between certain locations. Best practices for allowable movement will be further developed.
Source Bird
Island A
Island B
Island C
Drought
Tsunami
Sea level
Hurricane
Climate

Figure 3.



All management actions (some translocations more expensive than others, e.g., with predator mgmt)
Budget
Social palatability
Translocations requiring predator control
Island-specific variability in habitat quality (random distribution)
Probability of disease introduction: island/disease-specific effects (different durations)
IMPORTANT UNCERTAINTY: DIFFERENT MODELS FOR RISK OF MOSQUITOES
Vegetated area of island
LADU carrying
Disease
Weather catastrophes: Tsunami, hurricane
Extract from other populations as function of distance/status
Captive propagation
LADU extraction (only if pop'n in good shape, likely minor/no effect) on
Add LADU to Island A
LADU abundance & persistence on Island A
Random variation in translocation establishment
Predators: alien & native (no LADU introductions if alien predators present)
Sea level: function of time
IMPORTANT UNCERTAINTY: DIFFERENT MODELS FOR RATE & MAGNITUDE OF RISE
Random risk of predator introduction: function of island size, complexity, remoteness
IMPORTANT UNCERTAINTY: DIFFERENT MODELS FOR TIME TO ERADICATION
Hybridization: random chance on some islands
IMPORTANT UNCERTAINTY: REDUCE THROUGH RESEARCH

Figure 4.