Structured Decision Making

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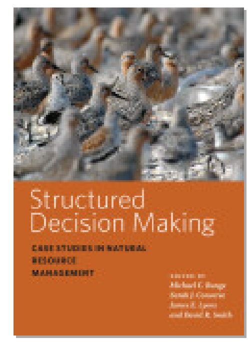

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Keeping Hawai'i's Forest Birds One Step Ahead of Disease in a Warming World

Hawai'i's high-elevation forests provide a critical refuge from disease for native forest birds. However, global warming is facilitating the encroachment of mosquitoes and the diseases they transmit into increasingly higher elevations of remaining refugia, threatening the viability of the forest birds across the islands. Multiple management actions to address the threat of disease have been proposed, but there is an urgent need to identify which actions (or series of actions) should be prioritized as most effective, most cost-efficient, and most likely to produce results at a pace sufficient to stay ahead of climate change. A group of scientists, managers, and policy makers convened to evaluate a set of possible conservation strategies under a structured decision-making framework, focusing on management of Hakalau Forest National Wildlife Refuge, which was established to protect native Hawai'ian forest birds. The biological models necessary to evaluate the set of conservation actions identified are not yet available, but the process of developing the framework for the decision analysis was immensely valuable for framing the issues and identifying information needs. Lessons learned from Hakalau Forest will be applicable to many other areas in Hawai'i facing the same threat to forest birds.

Problem Background

Hakalau Forest National Wildlife Refuge (Hakalau) was created specifically to be a high-elevation refuge for Hawai'ian forest birds and their habitat, including 3 endangered species, with a mandate to protect these threatened birds as well as all the native species the refuge harbors. Hakalau provides a critical refuge for native birds from vector-borne diseases and is one of the only places in the state where native forest bird populations are stable or increasing (Camp et al. 2010, 2015). Unfortunately, global warming is predicted to facilitate the encroachment of mosquitoes and diseases into increasingly higher elevations of the refuge while intensifying disease at lower elevations (Liao et al. 2015), requiring urgent conservation strategies to mitigate the threat. However, conservation strategies are constrained by uncertainty on effective management responses, limited budgets, land availability (e.g., jurisdictional issues and habitat availability), and public perception and cooperation. As a result, a process for developing and comparing alternate management actions at Hakalau is needed to preserve the refuge's native birds from avian disease and other threats. While refuge managers have direct control over on-the-ground actions at the refuge, some actions require cooperation from surrounding land managers and the community. Actions to confront these threats to native bird populations may need to be started now, even though the actual peril could be years in the future. The 2 key uncertainties to this issue are the speed at which disease will intensify or move up in elevation and the effectiveness of various management actions in slowing or preventing the incursion of disease or increasing resiliency of existing populations to disease. Although these management strategies will apply specifically to Hakalau and to surrounding landholdings, lessons learned from Hakalau should be applicable to other areas in Hawai'i facing similar threats to their forest birds.

Decision Maker and Their Authority

The decisions on which management actions to implement at Hakalau ultimately rest with the refuge manager. Hakalau exists to protect native fauna and flora within its boundaries and surrounding areas and must conduct management actions consistent with the preservation of native bird populations as typically required by policies and rules the refuge must act under. Multiple executive orders and legislative acts apply to the management of Hakalau, including at least 11 broad federal regulatory requirements, specific rules governing National Wildlife Refuges, and guidance specific to Hakalau. These rules and regulations provide a multitiered policy framework designed to guide refuge management. However, the spatial scale at which many possible management actions should be conducted exceed the boundaries of the refuge, and therefore neighboring land managers also make decisions that could influence the ultimate outcome of the problem.

Ecological Background

The Hawai'ian Islands have evolved a highly endemic avifauna as a result of geographical isolation, diverse topography ranging from sea level to mountains exceeding 4,000 meters above sea level (m asl), and habitats ranging from tropical lowland rain forests to subalpine tundra to deserts over distances as small as 40 km. Native Hawai'ian forest birds have experienced one of the highest rates of extinction in the world (Banko and Banko 2009) because of habitat loss and the introduction of alien plants and animals. While the conservation efforts to date have been substantial and have achieved successes, the scale of action has not matched either the scale of the threats or the conservation goals. Unfortunately, we are losing, not gaining ground in the race against extinction. In the past 25 years, 10 species of endemic Hawai'ian birds have been lost to extinction, and only 24 of the 46 historically known forest bird species still survive, with 13 listed as endangered (Banko and Banko 2009) and the entire community on Kauai rapidly declining (Paxton et al. 2016).

Today, most Hawai'i forest birds are restricted to high-elevation forests (over 1,500 m asl) largely as a result of 2 major factors. First, most low-elevation native habitats have been lost or heavily degraded, leaving remaining intact lowland forests scattered and fragmented. Secondly, introduced diseases, specifically avian malaria and avian pox, along with an introduced mosquito (southern house mosquito, *Culex quinquefasciatus*) that efficiently transmits these diseases (LaPointe et al. 2005), have largely displaced susceptible native birds from low-elevation forests where disease transmission occurs throughout the year (Atkinson and LaPointe 2009; Samuel et al. 2011) and many species in midelevation forests where disease is seasonally epizootic (Atkinson and Samuel 2010). These elevational disease patterns are driven, in part, by the effects of temperature and rainfall on mosquito dynamics (Ahumada et al. 2004; Samuel et al. 2011) and sporogonic development of the avian malaria parasite (*Plasmodium relictum*) within the mosquito vector (LaPointe et al. 2010) across an elevational gradient. The threshold temperature for malarial development is 13°C, which coincides with the 1,800 m asl elevation contour (mean annual temperature); this temperature threshold creates a disease-free refuge in forests above approximately 1,800 m asl (Atkinson and LaPointe 2009; Benning et al. 2002). At elevations between 1,500 and 1,800 m asl (corresponding to 13–17°C), seasonally favorable conditions can allow disease transmission to occur, typically in the late summer and fall (LaPointe et al. 2010).

Because avian malaria and pox are primarily spread through mosquitos, distribution and abundance of mosquitoes are key to understanding the distribution of these avian diseases. In most mid- and high-elevation Hawai'ian forests, *Culex quinquefasciatus* populations are limited by the availability of aquatic larval habitat; on Hawai'i Island this is primarily rain-filled tree fern (hapu'u) cavities created by foraging feral pigs and rock pools along the margin of intermittent stream beds (Atkinson and LaPointe 2009). Unmanaged artificial water impoundments can also contribute significantly to available larval habitat (Reiter and LaPointe 2009). Approximately 95% of Hakalau lands lie at elevations above the 17°C isotherm for seasonal disease transmission, effectively creating a refugia from year-round disease, although periodic disease outbreaks may occur in the lower and mid parts of the refuge (Freed et al. 2005; VanderWerf 2001). Thus, the refuge (fig. 4.1) preserves habitat for limited but stable populations of 3 endangered forest birds, the Hawai'i 'Akepa (*Loxops coccineus*), Hawai'i Creeper (*Oreomystis mana*), and Akiapola'au (*Hemignathus*

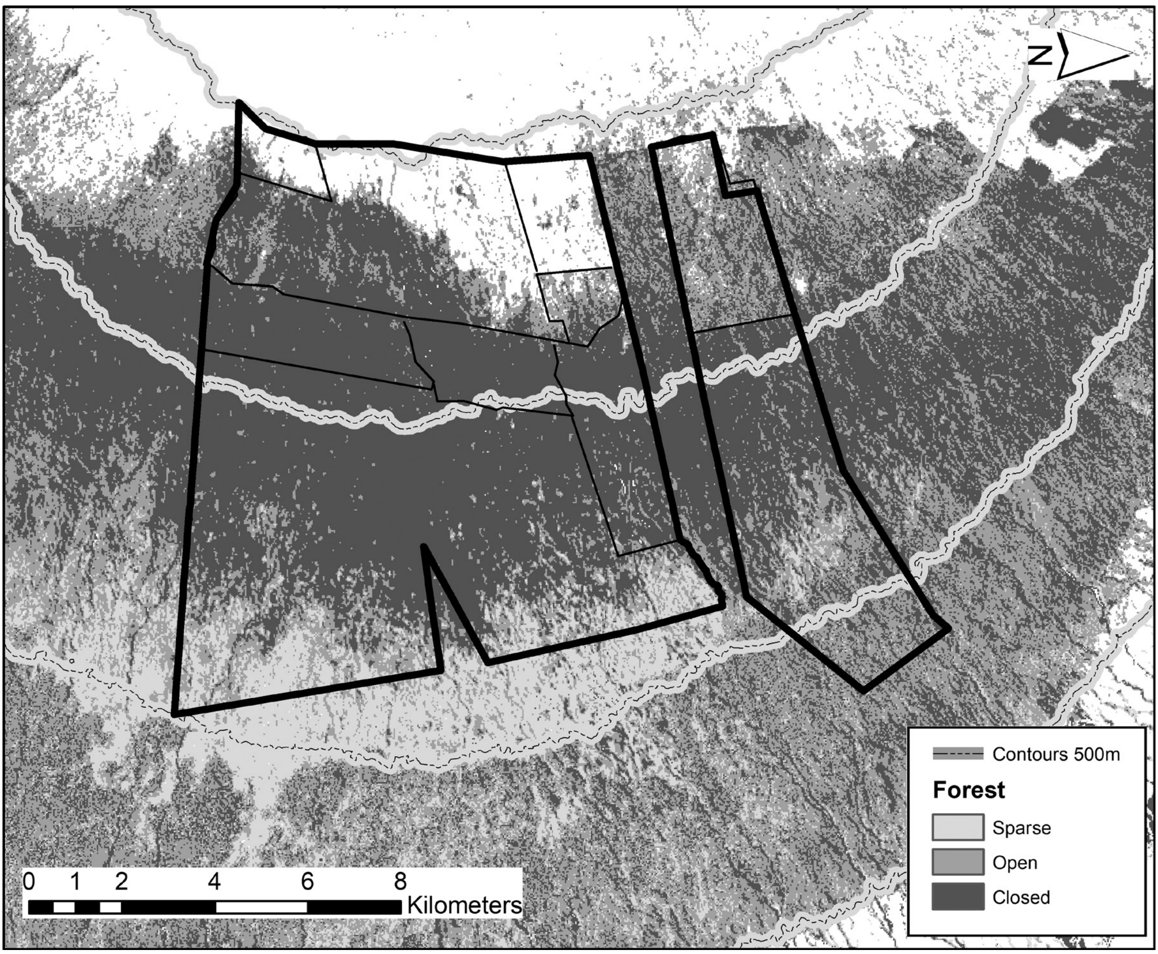

Figure 4.1. Map of Hakalau Forest NWR (thick black lines) and its management units (thin black lines). Light gray areas within the refuge are actively forested with koa trees. Active ungulate control occurs in the upper units. Area between the 2 parcels is Piha Forest Reserve. The 13,355 ha Hakalau was created in 1985 to protect rainforest that supports endangered forest birds. Located on the windward slope of Mauna Kea Volcano on Hawai'i Island, the refuge contains some of the best remaining examples of native rainforest in the state.

munroi) as well as larger populations of non-endangered I'iwi (*Drepanis coccinea*), 'Apapane (*Himatione sanguinea*), Hawai'i 'Amakihi (*Chlorodrepanis virens*), Hawai'i 'Elepaio (*Chasiempsis sandwichensis*), and Oma'o (*Myadestes obscurus*) (Camp et al. 2015).

Because temperature is a critical element in Hawai'i's disease-bird cycle, global warming is considered a grave threat to the disease-free sanctuaries of high-elevation forests for native forest birds. Currently, disease exposure in Hakalau forest birds is limited in the upper elevations, with a 2012 survey of avian malaria exposure (based on sampling blood from wild birds) indicating highs of 14% in Oma'o and 9% in 'Apapane but low to zero levels in the remaining species (LaPointe et al. 2016). Surprisingly, prevalence of malaria was significantly lower in 2012 (4.9% out of all birds sampled) than 1998 (12.4%), the last period that birds were sampled for avian malaria in Hakalau. In addition, of 1,004 birds examined, 5% had evidence of active avian pox infections (LaPointe et al. 2016). However, temperatures are rising, particularly at higher elevations (Diaz et al. 2011), and recently developed downscaled climate change models predict a temperature increase of 2.5°C or more across Hawai'i by 2100 (Zhang et al. 2012). The increasing temperatures will effectively eliminate this high-elevation transmission-free habitat within the current boundaries of the refuge (Benning et al. 2002), with expected profound negative effects on forest bird populations in Hakalau and across the Hawai'ian Islands (Fortini et al. 2015; Liao et al. 2015). However, recent evidence of disease resistance in native Hawai'ian forest birds (Atkinson et al. 2014; Woodworth et al. 2005) demonstrates that at least some species, in at least some areas, are developing resistance or tolerance to disease, and there is hope for similar evolution occurring in other species and populations.

Structuring the Decision

A group of 12 researchers, managers, and policy experts (see Acknowledgments) came together in 2011 to develop strategies for managing the looming problem of climate change and disease in forest birds. The group identified multiple objectives and developed alternative management strategies that encompassed a range of identified conservation actions. The biological models necessary to evaluate the alternative management strategies do not yet exist, but the process was immensely valuable for defining the problem, identifying key information needs, and providing a framework for how to move forward on addressing the issue.

Objectives

The primary objective was maintaining the abundance and diversity of forest birds at Hakalau. However, other objectives were identified as important and needed to be addressed. The 4 objectives were defined as follows:

1) Maintain each forest bird species at or above their current abundance. Our primary objective was to maintain (or increase) abundance of each native forest bird, which also implicitly ensures that current diversity is maintained on the refuge. Management actions would be assessed by using the most recent survey results (Camp et al. 2010, 2015) as a baseline to gauge alternative management strategies (table 4.1). We chose a 200-year period as the time scale, so that strategies were long-term in nature and would consider climate change and other long-term trends.
2) Minimize cost of management. The cost of alternative actions was identified as a key objective to recognize the reality that funds are limited and, all else being equal, the set of alternative actions that cost the least amount would be favored. Different management alternatives have different up-front and long-term costs (for example, building fences has significant upfront costs but comparatively low maintenance costs). We calculated costs for all sets of actions in a 15-year framework, which is about the typical refuge conservation plan cycle; these costs are approximations but give an indication of the spread of resources needed

Table 4.1. Abundance estimates with 95% confidence interval (CI) for native Hawai'ian forest birds at Hakalau Forest National Wildlife Refuge

Species	Scientific name	Abundance (95% CI)
Akiapola'au	*Hemignathus wilsoni*	575 (306–1,044)
Hawai'i 'Akepa	*Loxops coccineus*	11,012 (7,331–15,740)
Hawai'i Creeper	*Oreomystis mana*	13,106 9,276–17,626)
I'iwi	*Drepanis coccinea*	111,917 (94,078–130,165)
Oma'o	*Myadestes obscurus*	16,396 (12,583–20,836)
Hawai'i 'Elepaio	*Chasiempis sandwichensis*	18,196 (14,738–22,039)
'Apapane	*Himatione sanguinea*	77,811 (59,668–98,538)
Hawai'i 'Amakihi	*Chlorodrepanis virens*	48,691 (39,073–60,430)

Source: Camp et al. 2015.

Note: Objective 1 was to maintain populations at or above the current abundance levels based on the most recent survey results from 2012.

to achieve each alternative (table 4.2). Units for management costs were in US dollars.

3) Maximize probability of acceptance by the public. While the management alternatives that we considered are largely focused on the refuge, which could be conducted with a focus solely on refuge priorities, many actions would benefit from general public acceptance and cooperation with neighboring landowners. The refuge is surrounded by other landowners that have forest habitats adjacent to the refuge, and a conservation strategy that is adopted by neighboring land managers is likely to increase the success on the refuge. For example, a strategy that considered mosquito control through the application of a larvacide might require public input for the authorization stage. There are multiple approaches for measuring this means objective, including elucidating expert opinion, conducting surveys, or leading active outreach programs that measure attitudes toward different conservation actions.
4) Abide by all relevant legal statutes. The group realized that some actions might not be allowed under current law (e.g., aerial broadcasting of rodenticides to control rats), while other actions might indirectly violate other laws, such as spraying insecticides to control mosquitoes, which could harm endangered insects or run contrary to water quality regulations. Therefore, to constrain any possible actions into what is legally permissible, we identified the metric for this process objective as a simple binary yes/no.

Alternatives

To accomplish the primary objective (maintain current population levels of the 8 forest birds native to Hakalau for 200 years) in the face of rising temperatures and disease risk would require the adoption of new landscape-scale management initiatives of unknown efficacy. Without such initiatives, the disease-free area of the refuge would contract as global temperatures rise, until at some future time when no areas within the refuge boundary would be disease-free, and birds sensitive to disease would suffer population declines or local extinction. To prevent extinctions and extirpations, management actions are needed, such as providing new disease-free refugia, rendering existing habitat disease-free, or reducing the mortality of disease on native forest birds.

The group identified specific management actions that could be grouped into 4 broad categories, with associated costs. The groups of management actions included disease control approaches that were "low tech" (e.g., ungulate control, ungulate-proof fencing, mosquito control) and "high tech" (e.g., sterile male mosquito release, bio-engineered mosquitoes or *Plas-*

Table 4.2. Detailed breakout of costs associated with each alternative strategy over a 15-year time frame

Status quo	
Ungulate control ($175K/yr.)	$2,625K
Fence maintenance/replacement ($175K/yr. per 20-year replacement cycle)	$2,625K
Reforest koa ($75K)	$1,125K
Habitat enrichment ($75K)	$1,125K
New fencing (18.5 mi./5.6K additional acres)	$1,954K
Weed Control ($100K/yr.)	$1,500K
	$10,954K
A. Status quo + refuge-wide mosquito control	
Status quo	$10,954K
Additional ungulate control ($175K/yr.)	$2,625K
Additional fence maintenance/replacement ($175K/yr.)	$2,625K
Hapu'u cavity removal (eliminate larval habitat; $600K/yr.)	$9,000K
Streambed spray (treat twice/yr., $51K/yr.)	$765K
Heli-time ($775/hr. twice per yr., $15.5K/yr.)	$188K
Acquire or land swap for Piha GMU land	Unknown
	$26,157K +
B. Status quo + new mauka forest habitat (4,000 acres DHHL Humu'ula lands)	
Status quo	$10,954K
New fencing (10 miles @ 100K/mi.)	$1,000K
Fence replacement (50-year cycle/3x)	$900K
Ungulate eradication (DHHL 1yr. ungulate free)	$175K
Reforest koa and native understory ($2,000/acre)	$600K
Water system development	$1,000K
Cooperative management ($100K/yr. × 15-yr. joint restoration and coordination)	$1,500K
Weed control (DHHL $50K/yr. × 15 yr.)	$750K
	$16,879K
C. Status quo + disease compensation	
Status quo	$10,954K
Predator control ($200K/yr.)	$3,000K
Enrich natural food source ($75K/yr.)	$1,125K
Artificial food source ($50K/yr.)	$750K
	$15,829K
D. Status quo +building resistance	
Status quo	$10,954K
Augment native birds ($n = 20$/yr. @ $3,000 per; $60K/yr.)	$900K
Augment w/ disease-resistant birds ($n = 100$ @ $1,000 per; $100K/yr.)	$1,500K
	$13,354K

modium parasite). We also considered habitat manipulations (e.g., removal of mosquito larval habitat, reforestation of refuge or adjacent lands, removal of invasive weeds, enhancement of food resources) and population manipulations (e.g., removal of mammalian predators, augmentation of bird populations to increase genetic diversity, and translocation of individuals from disease-tolerant or -resistant populations to Hakalau). Finally, we considered land management arrangements that would help achieve conservation goals (e.g., comanagement with adjacent landowners, purchase of key land parcels).

Combinations of these actions resulted in 12 strategies, of which we considered 4 in detail (table 4.2), as they represented distinct approaches to addressing the looming conservation problem. These 4 new strategies assume continuation of the current management strategies and activities ("status quo"), but we felt it was important to explicitly consider the status quo (i.e., baseline management actions) as a standalone alternative action to quantitatively evaluate the consequences of "doing nothing." Each strategy varied in terms of the area affected (e.g., upper refuge, entire refuge), whether management was directed at improving habitat or directly targeted at bird populations, and whether cooperation with surrounding landowners was necessary. The strategies examined were:

- Status quo. Current management activities designed to benefit native forest birds at Hakalau, which are envisioned to continue for perpetuity, represent a baseline level of management effort. However, this strategy entails no additional action in the face of new threats from climate change, and as such we included it in the decision process to evaluate the added benefit of actively mitigating for the new threats, or the risks of "doing nothing."
    - *Area*: Current 8 fenced units for ungulate control, largely disease-free, 14,000 total acres in the upper portion of the refuge.
    - *Habitat management*: Reforestation of former pasture with koa and understory plant species, maintain fences and ungulate control efforts.
    - *Population management*: None.
    - *Co-management*: None.
    - *Cost (15 yrs.)*: $10,954,000.
- Reserve-wide mosquito kill plus. Strategy A aims to provide a disease-free safe haven by completely removing larval mosquito habitat from across the entire refuge. The mosquito-free area would be less than the total refuge area due to the ability of adult mosquitoes to penetrate some distance (approximately 1 km) from bordering unmanaged lands, but the reduction of disease transmission (regardless of temperature) would allow vulnerable species to expand or at least maintain their current distribution.
    - *Area*: Full refuge extent, 32,000 acres + intervening 4,000 acres in Piha, a state forest reserve lying between the 2 units of Hakalau.
    - *Habitat management*: Status quo actions plus new ungulate fencing and pig removal from lower portions of refuge, removal of artificial habitat for mosquitoes, larvicide treatment of streambeds and hapu‘u cavities.
    - *Population management*: None.
    - *Co-management*: Management of Piha State Forest Reserve consistent with refuge management.
    - *Cost (including status quo, 15 yrs.)*: $26,157,000.
- New refugia upslope. Strategy B would expand the forested area of the refuge upslope, providing more high-elevation, disease-free habitat to compensate for the encroachment of disease into lower areas of the refuge that are currently disease-free. This expansion is limited by the trade-wind inversion, which determines the tree line through precipitation and is expected to continue to confine forests below approximately 2,500 m (Cao et al. 2007).
    - *Area*: Current 8 fenced units (14,000 acres) for ungulate control in upper portion of refuge + 2,000 acres upslope of refuge.
    - *Habitat management*: Status quo actions plus new ungulate fencing, cattle and pig removal, reforestation with koa and native understory plants, removal of artificial mosquito larval habitat in new areas upslope of the refuge.
    - *Population management*: None.
    - *Co-management*: Co-management for wildlife with landowners of adjacent upslope lands.
    - *Cost (including status quo, 15 yrs.)*: $16,879,000.
- Disease compensation/facilitating evolution. Strategy C implements predator management and enhancement of food resources to increase survivorship, productivity, and carrying capacity for bird populations with the intent that the increase in demographic rates would offset disease-related mortality and decrease the risk

of population declines. One approach would be to target midelevation populations where there is moderate disease transmission, with the hope that disease-resistant or disease-tolerant genotypes may be more likely to survive and become more abundant in the population (Kilpatrick 2006). This action assumes that increasing the population size of native birds should slow disease-driven declines, providing time for disease resistance or tolerance to develop (Kilpatrick 2006).

  - *Area*: Focused on area of refuge with seasonal disease transmission (midelevation), which will vary over time.
  - *Habitat management*: Status quo plus enhancement of food resources through outplanting of understory and artificial feeders. Research would be needed to determine most effective approaches to enhance food resources.
  - *Population management*: Intensive suppression of mammalian predators, specifically trapping for rats to decrease nest predation and possible predation of incubating females.
  - *Co-management*: None.
  - *Cost (including status quo, 15 yrs.)*: $15,829,000.

- Building resistant genotypes. Strategy D uses a different strategy to promote the evolution of disease resistance. Translocations to the refuge would be used to maximize genetic diversity of resident bird populations and to augment their gene pools by introducing disease-resistant individuals from other populations.
  - *Area:* Entire refuge (32,000 acres).
  - *Habitat management:* Status quo, only in current 14,000 acres.
  - *Population management:* Translocate cohorts of all 8 species into refuge to increase genetic diversity, including the translocation of disease-resistant birds of any species with populations persisting at low elevations (e.g., Hawai'i 'Amakihi from the Puna district of Hawai'i Island).
  - *Co-management:* None.
  - *Cost (including status quo, 15 yrs.):* $13,354,000.

Consequences and Trade-Offs

The alternative strategies identified here represent different approaches to maintaining bird populations in the face of almost certain failure of the status quo approach over the long term. Identifying and describing key objectives and alternative strategies to address this problem was a major accomplishment of the group, and the clarity brought from that effort has helped guide subsequent discussions on how to mitigate the threat. However, formal assessment of the consequences and trade-offs of each alternative action requires a population model that can predict the potential outcome of each management action based on the changing rates of disease transmission over time. The model would need to be spatially explicit to account for refuge boundaries, management area effects, and impacts of bird and mosquito movement across the landscape. To evaluate strategies C and D would also require incorporating evolution of disease resistance as a submodel. Because many of the actions would take decades to have their full effect, the rate of temperature (and rainfall) change due to global warming is a critical variable in modeling the potential of each strategy to achieve the long-term objectives.

One of the major benefits of this process was identifying key gaps in knowledge that contribute to our uncertainty in how forest bird will respond to future climates and in the effectiveness of management actions to mitigate any negative changes. Since this effort began, several new studies have been conducted, many as a direct result of this decision analysis process that highlighted research needs. For example, Fortini et al. (2015) used recently developed downscaled climate projections for Hawai'i to develop climatic-based species distribution models for all forest birds and projected future distributions under 2100 climate conditions showing how the ranges of forest birds would severely contract as disease spreads into high-elevation forest. Liao et al. (2015) projected disease dynamics in future years on 3 species of Hawai'i honeycreepers by applying a detailed epidemiological model of the Hawai'ian forest bird disease system (Samuel et al. 2011) to downscaled climate models, highlighting that responses to changing disease distribution will vary among species. In addition, behavior differences among species can alter their risk to changing conditions, as Guillaumet et al. (2017) demonstrated by modeling landscape-level movements of the nectarivorous 'I'iwi in search of flowering trees that can take it to lower-elevation forests where disease occurs. Importantly, both the Liao et al. (2015) and Guillaumet et al. (2017) efforts developed models that link changing climate conditions to forest bird demographics, a class of models needed to fully evaluate the decision analysis presented in this chapter. Additionally, information on survival, recruitment (Guillaumet et al. 2015), and productivity (Cummins et al. 2014) provide the basic demographic rates needed to estimate population processes. Studies of forest bird populations in restoration forests (Paxton et al. 2017) provide important information on rates of colonization for proposed reforestation efforts.

Once the models are available to estimate the effects of alternative actions on our primary objective, we can move to the next step of choosing preferred alternatives in light of all objectives. The main approach we identified for conducting trade-offs is the SMART table (simple multi-attribute rating technique), where alternative actions could be assessed by how well they addressed the identified objectives (Gregory et al. 2012). Alternatively, a Pareto optimal set or efficiency frontier could be explored to choose alternatives that achieve the best ecological results for least cost (Keeney and Raiffa 1993). We also considered several approaches to incorporating the considerable uncertainties in this complex system. One approach would be to use a sensitivity analysis within a trade-off analysis, where predicted consequences for each alternative would be varied to see whether changes in expected outcomes would alter the overall decisions. If changes in the predicted consequences of an alternative strategy do not change the ultimate decision, then uncertainty does not matter for the purposes of making decisions. Likewise, the trade-off analysis could be conducted under a reasonable range of different climate change scenarios, each with their own predicted environmental responses. If the decision outcome were the same under the different climate scenarios, then climate change uncertainty could be removed from the decision process. However, if the sensitivity analysis indicated that different climate scenarios would affect the decision process, then climate change uncertainty would need to be considered when deciding which alternatives to adopt.

Discussion

Developing long-term conservation strategies to maintain the viability of Hawai'i's forest birds requires addressing the substantial issues of avian disease, habitat degradation, and other negative effects from non-native plants and animals (Paxton et al. 2018). The conservation challenges are many (Pratt et al. 2009), and the window of opportunity to effectively act on behalf of Hawai'i's forest birds is rapidly declining (Paxton et al. 2016). A primary limiting factor in addressing these issues is the lack of funds to carry out many of the basic conservation needs (Leonard 2008), let alone implement new strategies. However, the identification of key management strategies, as identified here, will help prioritize scarce resources to maximize the conservation benefits.

While recent studies have increased our understanding of Hawai'i's forest bird dynamics in present and future climates, there is still tremendous uncertainty in what future conditions will be, how they will manifest themselves in Hawai'i, and what the ecological response will be (Fortini et al. 2015). We expect that temperature increases in Hawai'i will produce significant increases in malaria transmission throughout mid- and high-elevation forests. However, climate models are uncertain on changes in precipitation, which can result in unpredictable consequences for avian malaria (Atkinson et al. 2014). For example, in a drier future with fewer high-precipitation events, permanent streams on Mauna Kea may become intermittent and thereby provide more larval mosquito habitat, thus requiring more direct management. These climate uncertainties add to the uncertainties associated with the efficacy and feasibility of proposed management actions. A structured decision-making approach allows mangers to develop fully articulate and transparent strategies, with input from experts and stakeholders, which will be easier to explain and justify and can be easily modified as conditions change and new information is gained.

Value of Decision Structuring

Effective conservation of Hawaiʻi's forest birds will require close collaboration between researchers and managers to jointly identify threats and management responses, implemented at ecologically meaningful scales, and continue to work at reducing key uncertainties about the impacts of threats and the efficacy of management actions. A formal decision-analysis approach can help managers justify actions taken in the face of uncertainty and provide the foundation for adjusting strategies as new information becomes available in an adaptive management framework (Runge 2011). Ideally, future model developments and improvements can be embedded within an adaptive management process combining both research and management programs to continually improve our knowledge about system dynamics and simultaneously evaluate different conservation strategies. Therefore, an adaptive management approach may be the best long-term approach to facilitate the decision process given the many uncertainties (Nichols et al. 2011). At the end of a predetermined time period (e.g., 15 years), the models would be revisited to determine whether (1) the predicted conditions have changed and (2) the models should be updated with new and informative information. If so, then a revised set of models would be run for the next management period (e.g., 16–30 years).

What Advances Did Decision Analysis Provide for This Problem?

For the initial evaluation of this problem, a diverse group of scientists and stakeholders was convened, including an equal representation of decision makers with resource management backgrounds and scientists who develop new knowledge to aid decision makers' management decisions. The strategies identified by the group represent different approaches to maintaining healthy bird populations in the face of the almost-certain failure of the status quo approach over the long term. Formal assessment of these conservation strategies to accomplish the objectives still requires a biological model that can predict the potential outcome of each management action based on the changing distribution and intensity of disease over time. At the close of the workshop, the group was pleased with its progress but clearly recognized this was only the first step toward a more detailed process involving stakeholder meetings, acquiring new information to inform existing models, and developing new models for assessing evolution of disease resistance under different scenarios.

Resource managers have recognized the importance of addressing this issue to prevent further avian extinctions, but an overall sense of exasperation over the complexity and scale of the problem, coupled with limited financial resources for integrative research and adaptive management, has hindered progress in developing practical solutions. The effort described in this chapter represents the first time that resource managers and scientists sat at the same table to discuss and prioritize potential strategies to solve this problem—an important development in itself. Although this effort did not result in the immediate implementation of specific actions, it did help prioritize which management actions are likely to have the most beneficial impact on bird populations and where there needed to be more research to fill in knowledge and technology gaps. Having a plan to move forward, even if exact steps were still uncertain, provided a sense of hope and purpose.

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