1. **ADMINISTRATIVE:**
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   Project Title: Vulnerability of Hawaiian Forest Birds to Climate Change - Using Models to Link Landscape, Climate, Disease, and Potential Adaptation
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2. **PUBLIC SUMMARY:** The Hawaiian Islands are home to some of the world's most imperiled forest birds. Introduction of mosquitoes and vector-borne avian malaria are important factors in the historic decline and extinction of many endemic Hawaiian honeycreepers which are particularly susceptible to avian malaria. We used a model of forest birds, mosquitoes, and avian malaria to evaluate future impacts of avian malaria on these Hawaiian birds as a result of climate change. As climate warms during the 21st Century temperatures will favor increased mosquito populations and much higher transmission of malaria to endangered honeycreepers existing in high-elevation forests. We conclude that without significant intervention many native Hawaiian honeycreepers will suffer major population declines and/or extinction due to this increasing risk from avian malaria. Proposed strategies to mitigate the problem include mosquito population suppression using sterile males or incompatible males, release of mosquitoes which are genetically modified to prevent malaria transmission to birds (e.g., refractory mosquitoes), competition from other introduced mosquitoes, evolved malaria-tolerance in native honeycreepers, feral pig control to reduce mosquito larval habitats, and predator control to improve bird demographics. Because predicted transmission rates of malaria will be higher than currently observed, several conservation strategies including predator removal, competing vectors, and feral pig control were insufficient to maintain these important bird populations at current levels. In contrast, mosquito control strategies offer potential long-term benefits to high-elevation Hawaiian honeycreepers. The predicted higher rate of future disease transmission means that combined strategies will likely be needed to preserve endemic birds at mid elevation. The predicted climate changes are likely to have enormous impacts in high-elevation forests where current low rates of transmission create a refuge for highly-susceptible birds, mitigating malaria transmission should be a primary avian conservation goal. Strategies that maintain highly-susceptible honeycreepers (such as the Iiwi) in high-elevation forests will likely benefit many other endangered Hawaiian birds.
3. **TECHNICAL SUMMARY:** Key objectives of our research were to evaluate temporal and spatial changes in avian malaria as climate changes during the 21st Century, evaluate the likelihood of future Hawaiian honeycreeper extinctions, and evaluate the effectiveness/costs of conservation strategies to mitigate anticipated forest bird impacts. As noted elsewhere in this report we were able to evaluate the long-term impact of 3 alternative climate scenarios on the abundance of several Hawaiian honeycreepers for each of the major elevational zone on the Island of Hawaii. Our results predict dramatic population declines and potential extinction of species that are moderately or highly susceptible to avian malaria in both mid- and high-elevation forests. Population declines are expected to accelerate beginning about the middle of the 21st Century. We also evaluated the viability of alternative conservation actions aimed at maintaining honeycreeper abundance through the end of the century. The most successful strategies likely include mosquito suppression using large-scale releases

of sterile or incompatible male mosquitoes and/or use of refractory mosquitoes to prevent malaria transmission to birds. The results of our research quantify the potential future impact of malaria on native Hawaiian honeycreepers and will help guide future conservation efforts to protect the viability of these forest birds in the face of climate change. At the international scale our research helps to identify how future climate changes can impact wildlife disease processes and host populations by accounting for the effects of climate variables on physiological and demographic factors, such as the host's population size, pathogen susceptibility, host demographics, pathogen and vector dynamics, and geographic ranges. Our host-vector-parasite model provides a tool for understanding the long-term threats of vector-borne diseases in other regions. Avian malaria in Hawaii, given the great similarity to human malaria, may provide a seminal model to understand the environmental and ecological drivers of human malaria as well as an ideal setting for evaluating malaria control strategies.

4. **PURPOSE AND OBJECTIVES:** Geographic isolation from the mainland makes the Hawaiian Islands home for many endemic species of flora and fauna. A typical example is the Hawaiian honeycreeper with over 35 original species prior to human colonization. However, only 17 currently remain, most of which are endangered. The introduction of *Culex* mosquitoes and avian malaria are considered to be primary factors contributing to the bird population declines, restricted distributions, and species extinctions. Avian malaria dynamics are strongly influenced by climatic components, such as temperature and precipitation. The future climate changes (warming and rainfall) in Hawaii will likely cause avian malaria to expand its range and intensity by invading high-elevation disease refugia and increasing in magnitude at lower elevations, respectively. These changes are likely to compromise the effectiveness of current avian conservation strategies. Therefore, the main goals of our project were: 1) evaluate temporal and spatial changes in avian malaria under anticipated climatic change, 2) predict the likely impacts the changes in avian malaria transmission on Hawaiian forest birds, and 3) evaluate the effectiveness of alternative conservation strategies to mitigate anticipated impacts of malaria.

   We collaborated with climatologists to obtain three predicted temperature and precipitation scenarios based on different downscaled climate models (A1B, RCP4.5 and RCP8.5). Incorporating these anticipated climatic change projections in our disease model, we completed the first two tasks of our research project: the distribution and dynamics of avian malaria and the possible impacts on native forest birds from climate change scenarios. A scientific paper on these results was published in Global Change Biology. We have also completed an evaluation of alternative disease mitigation strategies (single and combinations of strategies) and have submitted a scientific paper on these results to the journal published by the Public Library of Science (PLoS ONE).

5. **ORGANIZATION AND APPROACH:** We evaluated the potential impacts of future climate change on malaria transmission and native Hawaiian honeycreepers using an ordinary differential equation (ODE) epidemiological model to estimate the daily changes in susceptible, infected, and recovered (SIR) birds and susceptible, exposed (latent), and infectious (SEI) mosquitoes over time. Briefly, the model incorporates the daily population dynamics of the vector – Southern House mosquito; the avian hosts–three endemic Hawaiian honeycreepers, Amakihi, Apapane, and Iiwi; and the avian malaria parasite. These three Hawaiian honeycreepers represent the largest populations of extant native birds with some of the highest survival rates of previously studied Hawaiian avifauna and a range of behavior, biology, disease susceptibility, and landscape mobility. To assess the potential long-term effects of climate projections on malaria epidemiology and Hawaiian

honeycreepers, we averaged the biotic characteristics (e.g., bird abundance and mosquito larvae carrying capacity) for nine study sites for high-, mid-, and low-elevation forests.

We conducted a 24-year model run using historical weather patterns, estimated malaria-free bird densities, and one hundred infected adult mosquitoes per km^2 to generate initial state values for the model. Initial values were then used to conduct a 24-year baseline simulation from 1980-2003 using daily weather conditions to provide a realistic baseline of annual, seasonal, and daily climate variability. We used linear interpolation to gradually change these daily baseline patterns from 2004 levels to those predicted at the end of 21st Century for three alternative downscaled climate projections – A1B (warm and wet), RCP4.5 (warm and dry), and RCP8.5 (hot and dry). These 96-year simulations produced daily results of mosquito and bird density, prevalence of infected hosts and vectors, risk of malaria infection and other model parameters. We summarized the daily model results at 10-year intervals to facilitate interpretation of long-term trends.

We used the relative change in bird abundance (R = bird abundance at 2100 / bird abundance in 2004) to evaluate the performance of alternative malaria mitigation strategies. Successful conservation strategies have $R \geq 1$, which allows current bird populations to persist. Because our results showed that future Apapane populations were relatively stable regardless of the climate scenarios, we focused our evaluation on Amakihi and Iiwi at high and mid elevation. Of these species, Iiwi are highly sensitive to avian malaria and provide a likely surrogate for other endangered birds that now only reside at high elevation where current avian malaria infection is minimal. Simulations were performed using the ode45 solver in Matlab version R2011b. Liao et al. (2015) provides further details on modeling, climate projections, and additional references.

6. **PROJECT RESULTS:** We utilized a comprehensive epidemiological model of the Hawaiian bird-mosquito-malaria system to evaluate spatial and temporal effects of avian malaria transmission on Hawaiian honeycreepers under three future climate projections. The model predicted bird populations will decline due to more frequent and intense avian malaria transmission caused by global climate change during the 21st Century. The magnitude of population impacts varied with elevation, species susceptibility, species demography, and climate projections. A projected 2–5°C increase in ambient temperature lengthens the seasonal period for malaria transmission and increases disease prevalence in high-elevation forests (Figure 1) enabling avian malaria to become established in these high-elevation disease refuges. These events lead to native Hawaiian forest bird declines and potential extinctions, especially among malaria sensitive species such as Iiwi, which are predicted to decline by 70–90% (Figure 2). Although the temperature is a major driving factor for avian malaria transmission, projected changes in rainfall also play an important role in future malaria transmission, especially in high-elevation forests. For example, malaria transmission and bird impacts were similar for the warm and wet (A1B) climate projection compared to the hot and dry (RCP8.5) projection. Although temperature projections were similar, transmission and bird impacts were much lower for the dry (RCP4.5) compared to the wet (A1B) climate projection. Persistence of Iiwi populations, and other malaria-sensitive Hawaiian honeycreepers, in high-elevation forests may strongly depend on whether future climate patterns are hotter and wetter than current conditions. By analogy, we suspect many other native Hawaiian species that currently survive only in high-elevation forests also have high susceptibility to avian malaria and therefore may be in similar peril. Species of intermediate susceptibility, such as Amakihi and Apapane, may be slightly to moderately affected by future climate influence on malaria transmission at different elevations. Regardless of the climate projection, higher malaria transmission, avian population declines, and further restrictions in species distributions

are predicted by the model at both mid and high elevations and this is consistent with previous qualitative predictions of avian disease transmission.

Figure 1. Predicted annual malaria transmission rate during the 21st Century for three climate change projections (A1B, RCP4.5, RCP8.5) at (a) high, (b) mid, and (c) low elevations.

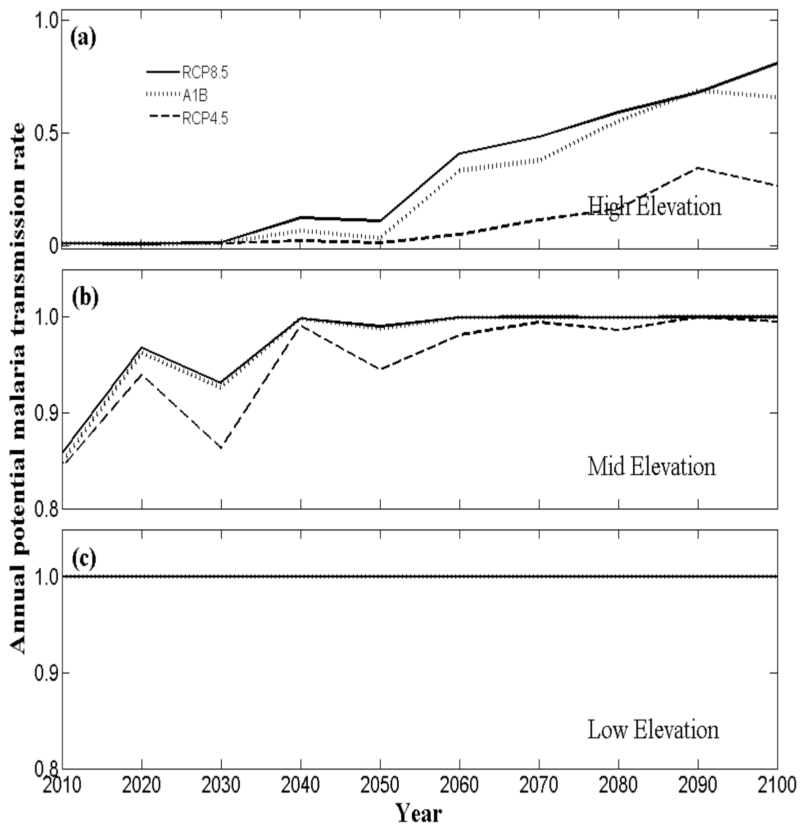
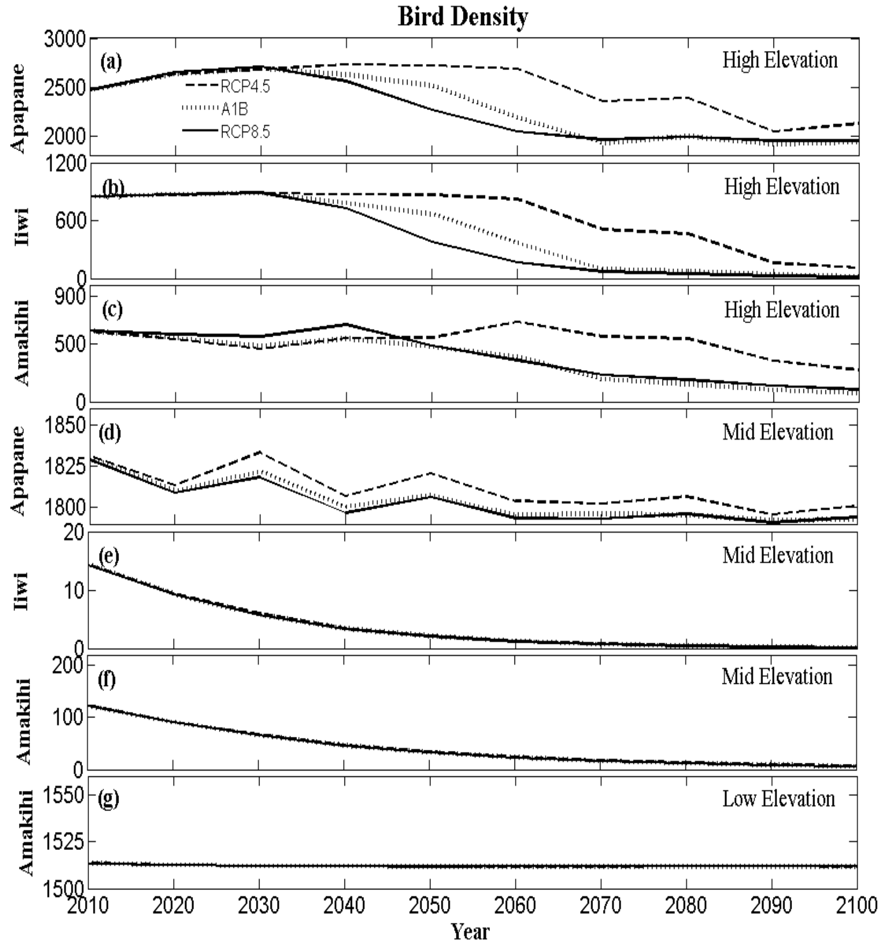


Figure 2. Predicted 10-year mean densities during the 21st Century of three Hawaiian honeycreepers (Apapane, Iiwi, and Amakihi) under three climate change projections (A1B, RCP4.5, RCP8.5) for high and mid elevations, and for malaria-tolerant Amakihi in low-elevation forests.



On the optimistic side, increased malaria infection and avian population declines, especially at high elevation, were not evident until near 2040. This delay provides a few decades for managers to develop and implement conservation strategies to mitigate malaria impacts. However, many of the potential conservation strategies including forest restoration, pig control, landscape scale vector control, and predator management will require both long-term planning and landscape scale conservation actions over an extended period of time. Because predicted climate changes are likely to have larger impacts in high-elevation forests where current low rates of transmission create a refuge for highly-susceptible endangered birds, mitigating malaria transmission should be a primary conservation goal at high elevation. Conservation strategies that maintain highly-susceptible species like Iiwi in high-elevation forests will likely benefit other endangered Hawaiian honeycreepers that are currently only found in these high-elevation forests. Proposed strategies include mosquito population suppression using sterile or incompatible males, release of genetically modified refractory mosquitoes to reduce transmission of malaria to birds, competition with *Culex* mosquitoes from other introduced mosquitoes, evolved malaria-tolerance in native honeycreepers, feral pig control to reduce mosquito larval habitats, and predator control to improve bird demographics. Because predicted transmission rates of malaria will be higher than currently observed, several conservation strategies were insufficient to maintain forest bird populations at current levels. However, mosquito control strategies offer potential long-term benefits to high-elevation Hawaiian honeycreepers. In contrast, integrated actions that use combined strategies will likely be required to preserve endemic birds at mid elevation where malaria transmission will increase substantially. Given the delay required to research, develop, evaluate, and improve many of these conservation strategies we suggest that planning and implementation should begin in the very near future.

Understanding how future climate impacts disease processes and wildlife populations requires incorporating the effects of climate variables on numerous physiological and demographic factors, such as the host's population size, pathogen susceptibility, host demographics, pathogen and vector dynamics, and geographic ranges. Our host-vector-parasite model includes these considerations and thus provides a useful tool for understanding other vector-borne wildlife diseases emerging in different regions. Avian malaria, given the great similarity to human malaria, may provide a seminal model to better understand the environmental and ecological drivers of human malaria. In the absence of human intervention, our model illustrates how climate change may impact future altitudinal malaria transmission patterns, which are crucial in evaluating climate and non-climate effects on fundamental properties of vector-borne diseases. Our predictions, that future avian malaria will expand its geographical range into cool, high-elevation forests, agrees with recent studies regarding human malaria distribution due to climate change – a warmer future will be more suitable for malaria transmission, and will increase the health burden in tropical highland regions. Emergence and reemergence of infectious vector-borne diseases, such as malaria and dengue, due to anthropogenic climate change, not only pose challenges for global health (including wildlife, domestic animals, and humans), but also has substantial economic costs associated with disease control. We believe the avian malaria system in Hawaii presents an ideal testing ground for the evaluation of potential strategies for combating avian and human malaria as well as similar vector-borne diseases.

7. **ANALYSIS AND FINDINGS:** Our modeling results show that future climate change in Hawaii will be very favorable to *Culex* mosquitoes, as well as the malaria parasite, and therefore increase the distribution and intensity of malaria transmission to native Hawaiian honeycreepers. In mid-elevation forests malaria transmission is expected to increase in intensity and occur for longer seasonal time periods, with nearly year round transmission by 2100. At high elevation, malaria transmission is predicted to have stronger seasonal peaks, longer periods of infection, and increased intensity. As a result, susceptible native species, such as Iiwi, will likely be extirpated from mid-elevation forests and are expected to decline dramatically in high-elevation forests. Similar population declines and possible extinctions are likely to occur in other endangered Hawaiian honeycreepers that are currently only found in high-elevation disease refuges. In addition, moderately-susceptible species, such as Amakihi, will experience substantial population declines, especially in mid-elevation forests as malaria transmission increases beginning about mid-century. Large scale conservation actions that address the issues of mosquito abundance and malaria transmission will be needed to preserve the diversity and abundance of native Hawaiian honeycreepers. Our evaluation of potential mitigation strategies shows that large scale release of sterile or Wolbachia infected male mosquitoes or the use of refractory mosquitoes that block transmission of malaria parasites to birds are potentially viable long-term strategies to control future malaria transmission, especially at high elevation. Evolution of malaria tolerance in native birds, as exhibited by low-elevation Amakihi, would also provide a potential means for sustaining native bird populations, but the likelihood that many Hawaiian species

can develop malaria tolerance in the next few decades seems highly unlikely. Our results illustrate that current strategies which reduce mosquito abundance by controlling feral pigs will become less effective as climate warming becomes more favorable for mosquito dynamics and malaria transmission. At mid elevation combined strategies for malaria control (e.g., sterile mosquitoes and pig control) will likely be required to maintain native bird abundance.

Other important findings from our project are summarized as follows. First, we found that downscaled climate projections for Hawaii were crucial because of the steep topography of the Hawaiian Islands, dramatic effects of elevation on temperature and rainfall that affect mosquito dynamics and malaria transmission, and the elevational distribution of native birds. These patterns are especially evident on the Island of Hawaii. Second, we found that future rainfall patterns in Hawaii play an important role in predicting future patterns of malaria transmission. Future impacts on native birds were similar under climate projections that were either hot and dry (RCP8.5) or warm and wet (AIB). Third, our results show that malaria transmission to native Hawaiian birds will likely remain relatively stable until about 2040 when increasing temperatures cause increased malaria transmission and consequently reduce native bird populations. Fourth, at least 2 bird populations, low-elevation Amakihi and mid-elevation Apapane, are likely able to cope with future increases in malaria transmission. As a result, management actions will not be needed to protect these species. Instead, malaria management strategies that focus on saving highly-susceptible Iiwi populations, especially at high elevation, will likely be beneficial to many other endangered Hawaiian species that occur at high elevation. Thus, Iiwi can serve as an indicator for successful management intervention to preserve most native species. Fifth, our results show that several conservation strategies are unlikely to be successful in the long-term effort to control malaria transmission. The use of predator control to benefit avian demographics, use of competing mosquito vectors, and potential evolution of malaria tolerance in birds are unlikely to have long-term success. Other strategies which are currently beneficial, such as pig control, will become less effective as climate changes and therefore will need to be replaced by combined/integrated approaches to achieve malaria control. Sixth, we found that use of new gene manipulation technologies, such as gene therapy and/or de-extinction methods based on CRISPR genome editing, could potentially be applied to native bird species to produce malaria resistant populations. Although controversial this strategy could provide a promising approach to save many of the Hawaiian birds from future extinction.

8. **CONCLUSIONS AND RECOMMENDATIONS:** In this project we were able to predict the temporal and spatial changes in avian malaria transmission to Hawaiian honeycreepers throughout the 21st Century and the expected impact on native bird populations. Our results provide management and conservation agencies with a time line of potential impacts on these unique avian populations as climate changes. In addition, we evaluated a number of alternative management strategies to mitigate the potential impacts on these birds. Our results identify both intermediate and long-term strategies that are likely to provide viable solutions to mitigate malaria transmission in Hawaii and maintain abundant honeycreeper populations. These results will help guide the development and timing of future malaria management strategies and direct limited resources towards optimal management strategies and focused research that will provide long-term solutions to this significant conservation problem.

In this project we were able to provide different predictions for malaria transmission and bird impacts for the three major elevational zones in Hawaii (low, mid, and high elevation). However, we were not able to translate these results into a spatially explicit map of future malaria risk across the eastern slopes of Mauna Loa on Hawaii. Production of spatially explicit risk data was difficult because we were lacking spatially explicit information on the abundance of mosquito larval cavities to make these predictions. In addition our project experienced unexpected delays during the first phase of the work due to delayed timing and miscommunication regarding the correct future climate predictions from the downscaled climate models. We also found that some of the climate model results provided unreliable future predictions for mid and high-elevation zones. As a result, we needed to develop alternative approaches to model trend projections for both temperature and rainfall.

Although our model of the forest bird-mosquito-malaria system is highly complex and strongly mechanistic it is unlikely to capture all the ecological intricacy of this biological system. Therefore, perhaps the best use of our modeling results is to compare relative trends in system predictions and behaviors, both with or without management intervention. As future management actions are developed and the science of climate change prediction improves we expect our model will be extremely useful in helping to predict outcomes of specific scenarios both for management actions and revised climate predictions. In addition, the model can be used in conjunction with specific management actions to validate model predictions and/or improve ecological relationships in the model. Overall we believe this model provides an important tool to help identify and guide the most promising research efforts and to complement adaptive management approaches to addressing the current and future threats of avian malaria to Hawaiian birds. One limiting aspect of our model is that populations of mosquitoes and birds are assumed closed at the spatial scale of 1 km^2. Future improvement should incorporate movement (seasonal and dispersal) of birds (especially Iiwi) and the movement of mosquitoes across the Hawaiian landscape.

9. **MANAGEMENT APPLICATIONS AND PRODUCTS:** Findings from our study provide important predictions about the future impacts of climate change and avian malaria on native Hawaiian honeycreepers. The results show that bird populations will be substantially diminished and extinction of some species is likely as climate becomes more favorable for mosquito populations and the transmission of avian malaria. Our results indicate that strategies that indirectly manage mosquito populations and/or evolution of malaria tolerance will likely be insufficient to maintain viable populations of many honeycreepers throughout the 21st Century. As a result, active mosquito management programs will be required to sustain many of these unique species. We show that using malaria-sensitive birds such as Iiwi as an indicator species to evaluate the success of management actions and outcomes is likely to provide successful protection of most other honeycreepers in Hawaii. Several mosquito suppression strategies appear to be viable options for preserving native honeycreepers in high-elevation forests, assuming that minimal performance criteria are met or exceeded for these strategies. However, future high malaria transmission rates in mid-elevation forests will likely require a combination of management strategies aimed at mosquito suppression and either feral pig or predator control programs. Given the extended time frame required to develop, evaluate, and implement these landscape scale management strategies, we suggest that the planning process begin relatively soon. Our results have identified those strategies that are most likely to be successful in the long-term so that research and management efforts can be directed at a reduced set of alternative strategies.

10. **OUTREACH:** Our outreach activities consisted of publications in the scientific literature, presentations at scientific conferences, and presentations to other scientific and management agencies. Details of these activities are listed below.

    Scientific literature:

Liao, W., O. E. Timm, C. Zhang, C. T. Atkinson, D. A. LaPointe, and M. D. Samuel. 2015. Will and warmer and wetter future cause extinction of Hawaiian forest birds? Global Change Biology doi:10.1111/gcb.13005.

Liao, W., C. T. Atkinson, D. A. LaPointe, and M. D. Samuel. Mitigating future avian malaria threats to Hawaiian forest birds from climate change. Submitted to PLoS ONE.

Guillaumet, A., W. A. Kuntz, M. D. Samuel, and E. H. Paxton. Altitudinal migration and the future of an iconic Hawaiian honeycreeper in response to climate change and management. Submitted to Ecological Monographs.

Presentations at scientific conferences:

Liao, W., and M. D. Samuel. How climate changes affect malaria transmission in Hawaiian forest birds – Preliminary evaluation. First PICSC/PICC Science Review Symposium. University of Hawaii – Manoa, HI. 15 July 2013.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. The effects of climate change on avian malaria and Hawaiian forest birds. Hawaii Conservation Conference, July 2014, Honolulu, HI.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. The effects of climate change on avian malaria and Hawaiian forest birds. Workshop on Regional Climate Change and Environmental Response in Hawai'i, July 2014, Honolulu, HI.

Samuel, M. D., C. T. Atkinson, D. A. LaPointe, B. L. Woodworth, W. Liao, and P. J. Hart. Disease in Hawaiian forest birds: current patterns and future threats. American Ornithologists Union Conference, Sep, 2014, Estes Park, CO.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. The effects of climate change on avian malaria and Hawaiian forest birds. The Wildlife Society Annual Conference, Oct, 2014, Pittsburgh, PA.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. Preliminary evaluation of mitigation strategies for avian malaria in Hawaii. 2015 Climate Science Symposium, Feb, 2015, Honolulu, HI.

Guillaumet, A., W. Kuntz, M. Samuel, and E. Paxton. Distributional patterns in I'iwi: seasonal movements and distribution of disease. Hawaii Conservation Conference, Aug, 2015, Hilo, HI.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. Preliminary evaluation of mitigation strategies for avian malaria in Hawaii. Conservation of Hawaiian Forest Birds Forum, Sept, 2015, Honolulu, HI.

Liao, W., M. D. Samuel, O. E. Timm, C. Zhang, C. Atkinson, and D. LaPointe. Conservation of endemic Hawaiian birds: evaluation of strategies to mitigate avian malaria in the face of climate change. The Wildlife Annual Conference, Oct, 2015, Winnipeg, Manitoba, Canada.

Presentations at other venues:

Samuel, M. D. Trouble in Paradise: Avian malaria and the demise of Hawaiian forest birds. University of Wisconsin, Student Chapter of the WDA, Wildlife Health Symposium, April 9, 2016.

Samuel, M. D., C. T. Atkinson, D A LaPointe, J. Liao, O. E. Timm, C. Zhang, T. W. Giambelluca, and H. F. Diaz. Trouble in paradise: Avian malaria, climate change, and the demise of Hawaiian forest birds. University of New York at Albany, April 21, 2016.

Liao, J., M. D. Samuel, M. D., C. T. Atkinson, D. A LaPointe, O. E. Timm, and C. Zhang. Trouble in paradise: Avian malaria, climate change, and the demise of Hawaiian forest birds. Webinar Pacific Climate Science Center, May 4, 2016.

Samuel, M. D., J. M. Liao, C. T. Atkinson, D. A. ,LaPointe, O. E. Timm, and C Zhang. Avian malaria, climate change, and mosquito control for Hawaiian forest birds. Webinar on Novel Vector Control Strategies and Status: Hawaii Wildlife Conservation Application. May 26, 2016.

Samuel, M. D., J. M. Liao, C. T. Atkinson, D. A. LaPointe, O. E. Timm, and C Zhang. Avian malaria, climate change, and the demise of Hawaiian forest birds. U.S. Fish and Wildlife Service, June 9, 2016, Honolulu, HI.

USGS News Release. July 16, 2015. As climate warms Hawaiian forest birds lose more ground to mosquitoes