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Use of high resolution lidar data to inform inter island translocation of endangered avian species in Hawaii

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Use of high resolution lidar data to inform inter island translocation

of endangered avian species in Hawaii

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Arts in Geography

by

Erica Marie Gallerani

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ABSTRACT OF THE THESIS

Use of high resolution lidar data to inform inter island translocation
of endangered avian species in Hawaii

by

Erica Marie Gallerani

Master of Arts in Geography
University of California, Los Angeles, 2022
Professor Thomas Welch Gillespie, Chair

Two Hawaiian honeycreepers endemic to Kauai, Akikiki (*Oreomystis bairdi*) and Akekee (*Loxops caeruleirostris*), are experiencing drastic population declines due to the spread of invasive disease exacerbated by climate change. We use habitat suitability modelling and high resolution lidar data to assess the potential management strategy of translocation to a novel environment. We transferred improved Maxent models based on topographic and forest structure metrics of the Alakai Plateau to native forest bird habitat on East Maui. Climate models previously developed for Akikiki and Akekee on Maui were used to restrict the lidar-based Maxent results. Additional models were produced for three endemic and native Maui species; Akohekohe (*Palmeria dolei*), Maui Alauahio (*Paroreomyza montana*) and Kiwikiu (*Pseudonestor xanthophrys*). Structurally suitable and climatically suitable habitat lined up well

for both Kauai species on East Maui. Canopy density was consistently the most important variable in the Kauai species models. Given the denser canopy and shorter vegetation structure metrics, East Maui favors Akikiki nesting habitat and Akekee general use habitat. We estimated an increase in Akikiki nesting habitat from the current Kauai range (13.09 km^2) to the range under future climate conditions on East Maui (23.43 km^2). The opposite is true for Akekee with a nesting range of 38.48 km^2 on Kauai and 26.29 km^2 on East Maui. To inform selection of potential release sites, we produced predictive nest and occurrence maps at the 100 m scale for Akikiki and Akekee on East Maui. Results from the Maui species models allowed for the assessment of potential niche competition between translocated individuals and species endemic to East Maui. Weighted overlap areas between the species from both islands were moderate (<12 km^2) and correlations between Maui and Kauai bird habitat were generally low. Results suggest that translocation to East Maui could be a viable option for Akikiki but would be more uncertain for Akekee.

The thesis of Erica Marie Gallerani is approved.

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Thomas Welch Gillespie, Committee Chair

University of California, Los Angeles

2022

TABLE OF CONTENTS

TABLES AND FIGURES

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1. INTRODUCTION

Avian malaria (*Plasmodium relictum*) is one of the primary drivers of native passerine species extinction across the Hawaiian Islands. Hawaiian honeycreepers, endemic to the archipelago, are particularly vulnerable to avian malaria, carried by the southern house mosquito (*Culex quinquefaciatus*) (Lapointe et al. 2012). Climatic factors such as rainfall and temperature are essential to the development of both mosquito vectors and the avian malaria parasite. Increases in temperature and decreases in rainfall during the wet season in Hawaii, caused by global warming, have enabled avian malaria to spread into higher elevations of the Hawaiian Islands (Fortini et al. 2020). Once present in lower elevations, the remaining native forest bird species of Hawaii are currently restricted to the highest elevation refugia free of the disease and its vector (Fortini et al. 2020). The situation on Kauai, the Hawaiian island with the most single-island endemic avian species, is particularly grave. The eight remaining native forest birds of Kauai are currently relegated to the upper elevations of the island in the ohia (*Metrosideros polymorpha*) forests of the Alakai plateau (Fricker et al. 2021). A recent study of honeycreeper vulnerability to avian malaria found that currently, the climate of the Alakai plateau is suitable for both vector and parasite sporogonic development most of the year (Fortini et al 2020). This greatly highlights the vulnerability of Kauai's native species to avian malaria given that five of the 13 historically present forest birds have gone extinct in the past 40 years (Reed et al. 2012, Paxton et al. 2018).

Akikiki (*Oreomystis biardi)* and Akekee (*Loxops caerulestrus)* are two critically endangered honeycreepers endemic to Kauai. Recent results from a systematic survey of the Alakai plateau in 2018 produced population estimates of 454 (95% CI: 120-886) individuals for Akikiki and 1,162 (95% CI: 643-1,698) for Akekee (Paxton et al. 2020). With an average decline of 11% per year, Akikiki and Akekee have experienced the steepest declines over the past few decades. The 2018 results also found a continuation of the trend of range contraction to the interior areas of the Alakai plateau (Paxton et al. 2020). In 2017, high-resolution light detection and ranging (lidar) data were acquired for the core habitat of Kauai's native forest birds over the Alakai plateau. Lidar derived metrics such as canopy height, canopy density and vertical distribution of biomass have been used to predict avian richness (Bakx et al. 2019). In previous research, topography and vegetation structure metrics derived from the airborne lidar data were employed in the creation of habitat suitability models for the Akikiki and Akekee (Fricker et al. 2021). Results from the models showed elevation was consistently the most important factor in determining suitable habitat for both species, further highlighting the need for mosquito management on the island. The models discovered important trends in habitat preference for two rare avian species and that translocation of captively bred individuals to higher elevation islands of Maui and Hawaii may be warranted (Fricker et al 2021). Indeed, there are locations on Maui (e.g. Hanawi Natural Area Reserve) and Hawaii Island (e.g. Hakalau Forest National Wildlife Refuge) where climatic conditions are not suitable for the development of both *Plasmodium relictum* and *Culex quinquefaciatus* (Fortini et al. 2020).

Translocation is the release of captively-bred or wild-caught species into new locations with the goal of successful establishment or re-establishment of an endangered species (Wolf et al. 1997). This conservation strategy falls within a suite of more radical approaches to managing the threats to imperiled species such as habitat loss, invasive species, and climate change (Schwartz and Martin 2013). While risky and often costly, this intentional movement of individuals form one area to another is a long-standing conservation practice with the potential for increased implementation due to climate change (Skikne et al. 2020). In 2017 Kauai Forest

Bird Recovery Project (KFBRP), and the San Diego Zoo established a captive breeding program for both Akikiki and Akekee (Greggor et al 2018). Therefore, these two critically endangered species are set up well for potential translocation with plans already in the works for Akekee (Berry et al. 2019). Managed relocation of the Akikiki and Akekee to refugia on higher elevation islands such as Maui could prevent future extinction while landscape mosquito control takes effect. However, the habitat quality of potential release areas on Maui has still not been identified and a number of avian studies suggest that this is a critical factor in translocation success (Wolf et al. 1997). Therefore, the use of habitat suitability analysis on potential release sites is necessary for the success of this radical tactic.

Eastern Maui, which consists of Haleakala National Park, private land, and several state managed Forest Reserves and Natural Area Reserves (NAR), is home to six native Hawaiian honeycreepers. Three of these species are endemic and threatened, Akohekohe (*Palmeria dolei*), Maui Alauahio (*Paroreomyza montana*) and Kiwikiu (*Pseudonestor xanthophrys*). Recent abundance estimations based on variable circular plot surveys and bioacoustics sampling place the Akohekohe (AKOH) at 1,768 ± 315 individuals with substantial declines over the past two decades. Abundance estimates for Maui Alauahio (MAAL) and Kiwikiu (or Maui Parrotbill, MAPA) are 99,060 ± 9,510 and 157 ± 67 individuals respectively (Judge et al. 2019). Most detections of these species occurred in elevations above 1,500 m where mosquitos and disease prevalence are reduced (Mounce et al. 2018, Fortini et al. 2020). The alarmingly low estimates for Kiwikiu bears similarities to the current dramatic declines in honeycreeper populations on Kauai Island (Paxton et al. 2016). These birds occur at such low numbers and densities that, based on expert opinions, competition with translocated species likely will not be a factor in species declines. Furthermore, East Maui once supported much higher forest bird densities with more species richness, including the Maui Akepa (*Loxops ochraceus*) closely related to the Akekee and last detected in 1988 (Judge et al. 2019).

The objective of this study is to determine if lidar-derived topographic and vegetation structure metrics could highlight suitable habitat for inter-island translocation of Hawaiian avifauna. First, using recently acquired airborne lidar data for the windward side of Maui, we transfer habitat suitability models for Akikiki and Akekee to East Maui. Based on previous research we assume that nest locations and occurrences of three threatened endemic Maui bird species Akohekohe, Maui Alauahio, and Kiwikiu, are associated with lidar derived metrics at two informative scales (10 m, 100 m). Second, we develop habitat suitability models for the three Maui species using one scale to capture microhabitats and one coarser scale to capture habitat patches. To determine the potential risk to the release ecosystem, we conduct an overlap analysis between all five species modelled. Third, we calculate and create habitat suitability and range maps for all five bird species. We predict that overall, overlap values will be moderate between Kauai species and Maui species with the highest overlap between occurrences for Akikiki and Alauahio and Akekee and Kiwikiu due to their similar foraging behavior (Vetter et al. 2012).

2. METHODS

2.1. Species Nest and Occurrence Data

Nest and occurrence locations were collected for all species using handheld Garmin Rino GPS units by experienced field workers. Kauai species data was collected from 2012 till 2018, building upon the previous data set used to create the Akikiki and Akekee models in Fricker et al. 2021. Kauai species location data were collected from two primary sites, Mohihi and Halepaakai and two secondary sites, Kawaikoi and Upper Kawaikoi all within well-known forest bird habitat at high elevations (~1250m to ~1300 m). Locations of these species were recorded by KFBRP field technicians during opportunistic encounters, nest searches, occupancy surveys and variable circular plot surveys during Hawaii Forest Bird Count years (2012, 2018). Maui nest and occurrence location data were collected by the Maui Forest Bird Recovery Project (MFBRP) using the same methodology as the KFBRP crew. The occurrences and nests for all species on Maui's windward side were concentrated in The Nature Conservancy's Waikamoi Preserve and the Hanawi NAR. Occurrence data were available for all three species, but nest locations were only available for Kiwikui (some nest locations were provided for Akohekohe, but not enough points were found within the GAO Maui coverage area).

2.2. Model Scale

Analyzing the interplay between various processes occurring at different scales is widely acknowledged by ecologists as essential to understanding observed patterns of species traits (Menge and Olson 1990). Fricker et al. (2021) used a multi-scale approach to explore habitat associations for Akikiki and Akekee across the Alakai plateau. Results from their study of 10 m (micro-habitat), 100 m (habitat patches), and 250 m (meso-habitat) scales found that the most descriptive scale for forest bird nests and occurrences was the 10 m and 100 m scale respectively. Finer scales tend to increase model performance as they allow for a more accurate representation of how local environmental conditions effect habitat suitability. However, finer scales may not always lead to optimal transferability (Manzoor et al 2018). While it has been found that finer scales are more appropriate for modelling rare species, an iterative modeling process, such as the one used here, can bypass this constraint (Draper et al. 2019). We therefore looked at 100 m scales for nests and occurrences when transferring models to Kauai. This scale performed well for all models on Kauai Island and is appropriate for the uncertain task of transferring models to novel habitat. Due to the accuracy of nest locations recorded for the native Maui species, we used a multi-scale approach when producing habitat suitability models for Kiwikui nesting and occurrence sites (10 m and 100 m respectively).

2.3. Lidar Data Collection

An Optech HA-500 dual channel airborne lidar system aboard the Global Airborne Observatory (GAO) was used to collect the lidar point cloud data over East Maui between January 12-14, 2018. During these dates, collection conditions were very good suggesting an absolute positional error of less than 10 cm given previous collections with this same equipment. Flights were performed at an altitude of 2000m above ground level and a speed of 130 kt. The lidar was configured to have a combined pulse density 200 kHz, scan frequency 34 Hz, and field of view set to 34 degrees. Given these parameters, we computed the point and pulse densities for every 2 m pixel in the coverage. This resulted in 99% of the coverage having point pulse densities between 0.97 and 13.8 pulses m^{-2} (1.95-37.19 points m^{-2}). Less than 0.03% of the total number of pixels recorded zero pulse returns in the area of interest. Upon visual inspection of these pixels, it was confirmed that a large share was over bodies of water (Global Airborne Observatory 2020).

2.4. Lidar Metrics

We computed metrics from the GAO lidar data to match the input variables used in the training of the Kauai MaxEnt models at the 10 m and 100 m spatial resolution. Initially, we analyzed the potential transferability of the Kauai lidar-based models to the Maui data by conducting a novelty analysis using command prompt tool Novel (Phillips 2017). These figures display that most of the novelty of Maui compared to Kauai is due to higher elevation values in the western portion of the East Maui area (Figure 1).

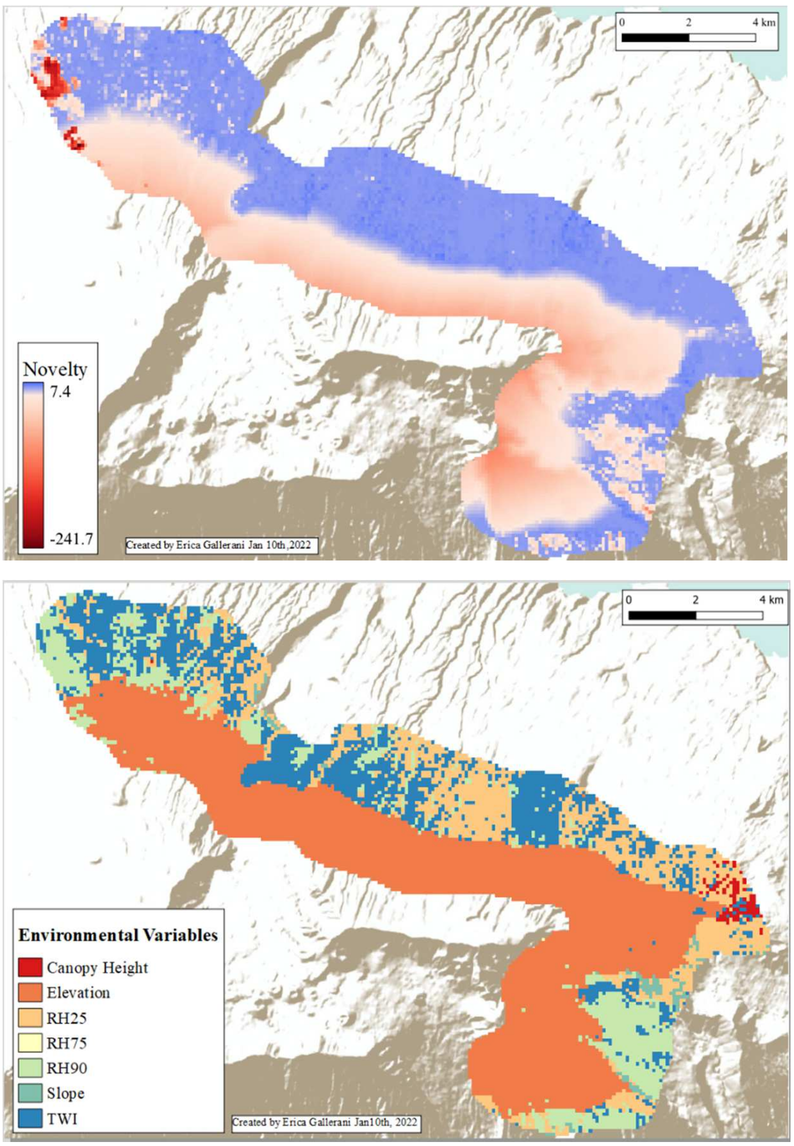


Figure 1. The novelty of topographic and forest structure values on Maui compared to Kauai. The top map displays how novel each pixel is with negative values representing novel pixels in red and positive values representing similar pixels to Kauai values in blue. The bottom map displays which variables are most novel in each pixel.

The other lidar variables which contributed most to increased novelty were relative height 25 and relative height 90 along with topographic wetness index. We compared the distributions of the 100 m resolution metrics derived from GAO data with the distributions of the same variables from the original Kauai training data to further determine how the two areas differed (Figure 2).

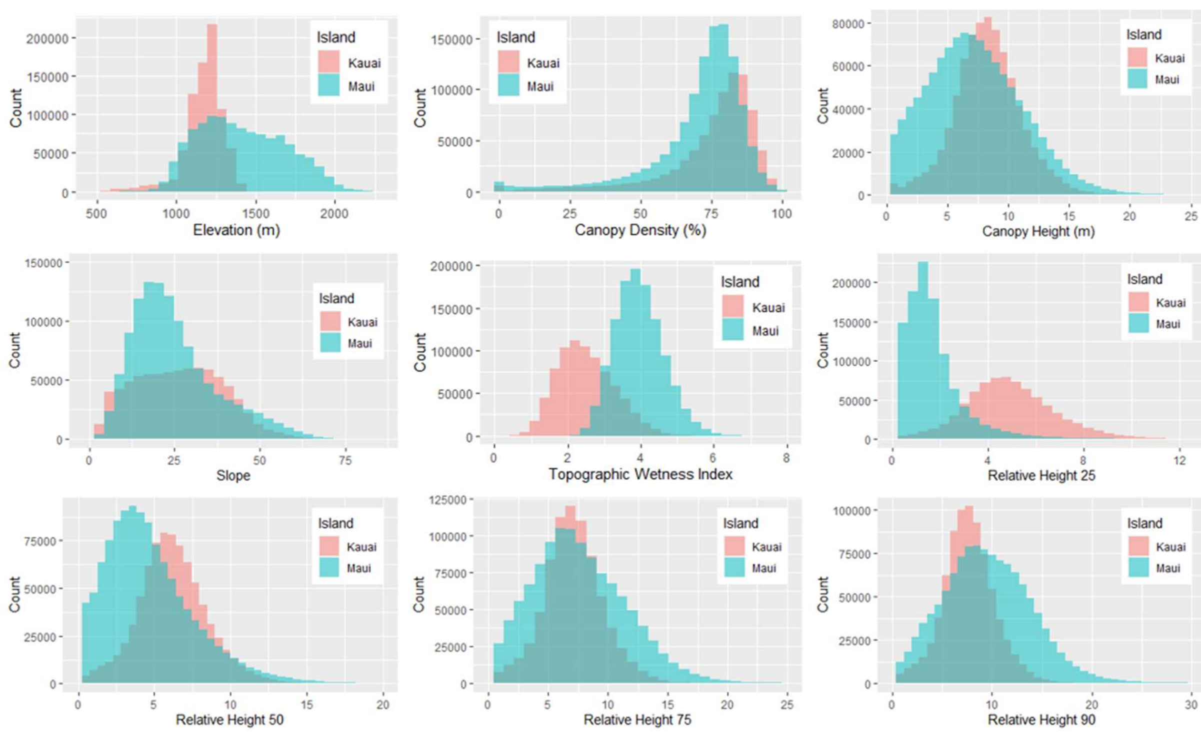


Figure 2. Paired distributions of the individual lidar-derived input metrics between the data used to train the Kauai MaxEnt models and the Global Airborne Observation (GAO) data used for applying the models on Maui.

In order to enhance the transferability of the Kauai models to Maui, we eliminated elevation as a metric in our analysis, as the Maui elevational range is much larger than that of Kauai. However, we know that under current pressure from avian malaria, elevation acts as a proxy for the presence of *Culex quinquefaciatus* and *Plasdium relictum* in avian habitat suitability modeling in the Hawaiian Islands (Fricker et al. 2021). To account for the presence of invasive disease, the results of the Kauai species' models will be constrained to areas found previously to be suitable for Akikiki and Akekee on East Maui under current and future climatic conditions. Collinearity is of particular concern in transferring models as the correlations between the variables may differ from the training site to the projection site (Manzoor et al. 2018, Duque-Lazo et al. 2016). We therefor ran a spearman rank correlation between the lidar-derived variables at the 100 m scale on Maui to determine collinearity (Table 1). We chose to eliminate variables with the most novel distributions on Maui that were also highly correlated to other lidar variables with similar distributions between the two islands (Table 2).

Table 1. Spearman rank correlation values associated with the nine lidar-derived topographic and vegetation structure metrics on Maui.

	Canopy Density	Elevation	Canopy Height	RH_{25}	RH_{50}	RH_{75}	RH_{90}	Slope	TWI
Canopy Density	1.000	0.004	0.645	0.527	0.599	0.616	0.404	0.165	-0.124
Elevation	0.004	1.000	0.040	-0.068	-0.029	0.019	0.027	0.135	-0.064
Canopy Height	0.645	0.040	1.000	0.726	0.936	0.967	0.619	0.066	0.000
RH_{25}	0.527	-0.068	0.726	1.000	0.805	0.696	0.431	0.059	-0.011
RH_{50}	0.599	-0.029	0.936	0.805	1.000	0.916	0.562	0.037	0.019
RH_{75}	0.616	0.019	0.967	0.696	0.916	1.000	0.640	0.098	-0.004
RH_{90}	0.404	0.027	0.619	0.431	0.562	0.640	1.000	0.114	-0.021
Slope	0.165	0.135	0.066	0.059	0.037	0.098	0.114	1.000	-0.597
TWI	-0.124	-0.064	0.000	-0.011	0.019	-0.004	-0.021	-0.597	1.000

Table 2. Lidar metrics used as input into the Kauai and Maui MaxEnt models.

Variable Name	Description
Canopy Density	Percent of lidar points > 1.37 m (4.5ft) above ground in the selected region.
RH_{50}	50^{th} relative height above ground for all lidar points in the selected region.
RH_{75}	75^{th} relative height above ground for all lidar points in the selected region.
Canopy Height	Height of the modeled canopy surface above ground in meters.
Slope	Slope derived from the elevation map.

2.5. Maxent Modelling

The Kauai models were rerun using the same maximum entropy software (MaxEnt version 3.3.4 k) as used for the original models in Fricker et al. (2021), for occurrence and nest locations from 2012-2018 at the 100 m spatial resolution. Given the smaller sample size of points for these bird species 100% of the nest and occurrence points were used to train the models. A bootstrapped resampling method was used to reduce overfitting, producing 100 submodels averaged to produce habitat suitability, with standard deviation outputs used to measure uncertainty. These model results were then applied to the GAO Maui lidar data using command line operators and inputs of the Kauai bird point data, lambda files from the Kauai models containing model parameters, and the Maui lidar-derived metrics (Phillips 2017). A similar procedure was used to build new MaxEnt models and maps for the Maui bird species using the same GAO lidar-derived metrics and nest locations and occurrence counts collected in the field (Table 3).

Table 3. Number of nest and occurrence samples within GAO coverage area used in the Maui species MaxEnt models.

Species	Data Type	Samples Within AOI
Akohekohe	Occurrence	587
Maui Alauahio	Occurrence	2758
Kiwikui	Occurrence	1042
Kiwikui	Nest	47

Methodology from Fricker et al 2021 was followed closely therefore, we insured that the Maui feature types were limited to linear, product or quadratic features as is recommended to reduce modeling complexity in presence-only modeling (Hagar et al 2020). The final settings used for the three Maui species matched those used by the Kauai models, i.e. a bootstrap replicant type and with 100% of samples used for training (Global Airborne Observatory 2020). To compare model performance, we looked at the area under the receiver operating characteristic curve (AUC) scores. AUC scores indicate how well the model ranks observations higher than random background pixels in presence only modelling (Radosavljevic & Anderson 2014). Given the nature of the terrain and topography in native bird habitat on Kauai and Maui, sampling tends to be spatially clustered around field sites. This sample selection bias wherein some areas are sampled more heavily than others, has a greater effect on presence only Maxent modelling (Elith et al. 2011). We therefore implemented background weight correction with the FactorBiasOut algorithm found in the Maxent GUI (Phillips et al. 2009). Using the 'Kernel Density' tool in ArcGIS we created rasters of sample selection bias or point density for all nest and occurrence point datasets for all 5 species at the 100 m scale. To give areas with a higher density of observations a greater selection probability, we applied a linear rescaling to each bias grid from zero to 20 (Elith et al. 2011). The rescaled kernel density rasters were then run through the same "PrepareDataforMaxent10.0" tool for ArcGIS.

2.6. Clipping to Climate Models

It is common practice for habitat suitability models to be built on a standard set of bioclimatic variables such as the 19 available in WorldClim at the 1 km resolution. The use of these standardized bioclimatic variables does not always lead to accurate predictions due to the coarse scale and unknown importance to species being modelled (Manzoor et al 2018). Often, finer scale land cover and topography metrics allow for more accurate fine scale habitat suitability modeling of avian species (Bakx et al 2019, Gogol-Prokurat 2011, Gottschalk et al.

2011, Manzoor et al 2018). Additionally, model transferability decreases as the number of environmental layers used to build said models increases, potentially leading to overfitting (Low et al 2021, Duque-Lazo et al. 2016, Radosavljevic & Anderson 2014, Yates et al 2018). In areas with rugged terrain like that on East Maui, microclimates are often dependent on fine scale topographic and vegetation structure features (Gogol-Prokruat 2011, Reinier de Vries et al. 2021). Coarser-scale climate data may not be able to properly define the microhabitats and refugia of species from trends in macroclimate (Franklin et al 2012). Therefore, we chose to exclude bioclimatic variables from our analysis and focus on lidar metrics. However, our previous knowledge of the native Hawaiian forest birds decline shows that climate variables are very important to invasive disease dynamics in the Alakai plateau (Lapointe et al 2012). Therefore, we use previously built climate models for Akikiki and Akekee to clip the results of our transferred models to incorporate the potential risk from avian malaria present on East Maui. Previous models built by Fortini et al (2017) determine present and future potential ranges for Akikiki and Akekee on East Maui. The climate predictors for these models reflect mean and variance of temperature and rainfall, factors that are very important to the development of both *Culex quinquefaciatus* and *Plasdium relictum* (Lapointe et al 2012). Future predictions were derived from Hawaiian Regional Climate Model Projections which predicts a warmer and wetter future for Hawaii (Zhang et al 2012). We use both the current climatically suitable habitat area that may be lost under future conditions and the range for both species that is stable under future climate conditions.

2.7. Overlap Analysis

To better understand how the endemic Maui species and translocated Kauai species would interact in the wild, we compared habitat suitability results between both sets of species. First, we conducted a spearman rank correlation test between the suitability predictions for each combination of species nests and occurrences. Second, used habitat suitability maps to compute weighted area of overlap to see which species might have the highest chances of interfering. These values were computed by multiplying the two suitability values for each valid pixel in the 100m resolution maps and converting to square kilometers by dividing by 100. The equation for this is as follows, where S_i is predicted suitability for pixel i and the summation is over all pixels with valid predictions for both species:

$$\frac{\sum_N \left(\prod_{i\in(1,2)} S_i\right)}{100}$$

2.8. Threshold Calculation

We estimate the range of all five species for nest sites and occurrences in East Maui by thresholding maps of predicted habitat suitability into presence and absence categories. These binary maps of presence and absence were determined based on a minimum training presence threshold (MTP). The MTP reflects the minimum Maxent value at which each species' nest or sighting occurred, resulting in areas that are at least as suitable to the species' current locations (Pearson et al. 2007). For the Kauai ranges on Maui, we used the same MTPs employed by Fricker et al 2021 and then derived the MTPs for the Maui species based on our Maxent model results.

3. RESULTS

3.1. Kauai Species on Maui

Kauai species models with a reduced list of Kauai environmental layers still performed well with AUC scores > 0.80. Canopy height had the highest percent contribution (38.5%) of the five variables to the Akekee nest models, with similar contributions from canopy density (27.6%) and Slope (19.7%) (Table 4).

Table 4. Percent contribution of each lidar-derived variable for the Kauai species nests and occurrence models at the 100 m scale.

		Canopy Height	Canopy Density	Relative Height 50	Relative Height 75	Slope
Akekee	Nests	38.5	27.6	7.8	6.4	19.7
	Occurrences	6	57.5	4.9	16.2	15.3
Akikiki	Nests	6.9	42.6	12.7	31.8	6
	Occurrences	6.5	68.7	4	15.3	5.4
	Mean Contribution	14.475	49.1	7.35	17.425	11.6

Canopy density had the highest percent contribution for the Akekee occurrence model (57.5%) and Akikiki nest (42.6%) and occurrence (68.7%) models. Additionally, canopy density had the biggest effect on regularized training gain of all four models. Of the models, Akikiki nests had the highest percent contribution from both relative height metrics with 31.8% contribution from relative height 75 and 12.7% contribution from relative height 50. The minimum training presence threshold from the original Kauai models were used to calculate ranges on East Maui. There are consistently higher potential ranges on Maui under current climate conditions than on Kauai (Table 5).

Table 5. Potential future ranges of Akikiki and Akekee based on both point types (nests and occurrences) on Maui compared to their current ranges on Kauai.

		Current Climate Range (km^2)	Stable Climate Range (km^2)	Current Range on Kauai (km^2)
Akikiki	Nests	53.37	23.43	13.09
	Occurrences	48.42	21.67	38.20
Akekee	Nests	54.49	26.29	38.48
	Occurrences	58.06	27.21	57.57

Restricting the model results to areas that are suitable under future climate conditions resulted in lower potential nesting and general use habitat ranges for the Kauai species on Maui than the current condition on Kauai, with one exception. The Akikiki has a higher nesting range under future climate conditions on Maui (23.43 km^2) than currently available on Kauai (13.09 km^2).

3.2. Maui Species Models

The Maui species models using the full suite of lidar-derived metrics (elevation, slope, topographic wetness index, canopy density, canopy height, relative height 90, relative height 75, relative height 50, and relative height 25) performed very well with AUC scores > 0.945 and low levels of uncertainty with standard deviation values < 0.010 (Table 6).

Table 6. Area under the receiver operating characteristic curve (AUC) score and standard deviation of predicted habitat suitability among the 100 replicates of each Maui species model.

		AUC Score	Standard Deviation
Kiwikui	Nests (10 m)	0.945	0.007
	Nests (100 m)	0.97	0.006
	Occurrences	0.954	0.003
Akohekohe	Occurrences	0.963	0.005
Alauahio	Occurrences	0.969	0.004

The 100 m scale performed better for predicting suitable nesting habitat for Kiwikui than the 10 m scale, conflicting with the results from the original Kauai models. Across all models, elevation had the biggest effect on training gain, followed by canopy height and relative height 90. Elevation had consistently the highest percent contribution for all species models across all scales and point types (48.7-72.8%). This was followed by canopy height which had the second highest percent contribution in almost all models except the Kiwikui 10 m nest model. At the finer scale, slope had a high percent contribution to the Kiwikui nest models (21.8%), while it had consistently low percent contribution to all other models (Table 7).

Table 7. Percent contribution of each lidar-derived variable to Maui species models.

		Elevation	Canopy Height	Canopy Density	RH_{25}	RH_{50}	RH_{75}	RH_{90}	Slope	TWI
Kiwikui	Nests (10 m)	50.8	18.1	3.9	0.6	0.2	1.6	2.1	21.8	0.9
	Nests(100 m)	48.7	11.9	2.2	1	7.9	6.8	10	9.5	2
	Occurrences	64.4	17.6	0.9	1.2	2.3	0.4	5.4	6.3	1.5
Akohekohe	Occurrences	72.8	10	1.2	0.1	2.2	0.5	9.2	3.1	0.8
Alauahio	Occurrences	58.4	16.8	8.3	0.1	5.5	1.7	7.4	8.3	0.9

The minimum training presence threshold (MTP) for the Kiwikui nest model at 100 m was 0.13 probability of predicted presence (Table 8). This resulted in a nesting range on East Maui for Kiwikui of 38.9 km^2. The MTP for the Kiwikui occurrence model was 0.13 as well and resulted in a general use habitat on East Maui of approximately 32.3 km^2. Akohekohe has a range on East Maui of 19.49 km^2 based on an MTP of 0.36 probability of predicted presence. Maui Alauahio has a MTP of 0.09 predicted probability of presence resulting in a range on East Maui of 32.43 km^2.

Table 8. Minimum Training Presence (MTP) threshold values and calculated ranges for the three Maui species on East Maui based on nests and occurrence model results at the 100 m scale.

Species		MTP	Range ($km^{2)}$
Akohekohe	Occurrences	0.362	19.49
Maui Alauahio	Occurrences	0.093	32.43
Kiwikui	Occurrences	0.129	32.34
	Nests	0.134	39.00

3.3. Overlap Analysis

Akikiki and Kiwikui nest habitat had the highest weighted overlap area on East Maui of approximately 11 km^2 (Figure 3). Kiwkui nesting habitat also experiences slightly larger weighted overlap area with Akekee nesting habitat on East Maui than the other Maui species of around 8 km^2. Maui Aluahio had the smallest weighted overlap area with the two Kauai species. The highest percentage of weighted overlap area to a Maui species range on East Maui occurred with Akekee and Akohekohe. The weighted overlap area of around 7 km^2 takes up around 36% of the Akohekohe range on East Maui of 19.49 km^2.

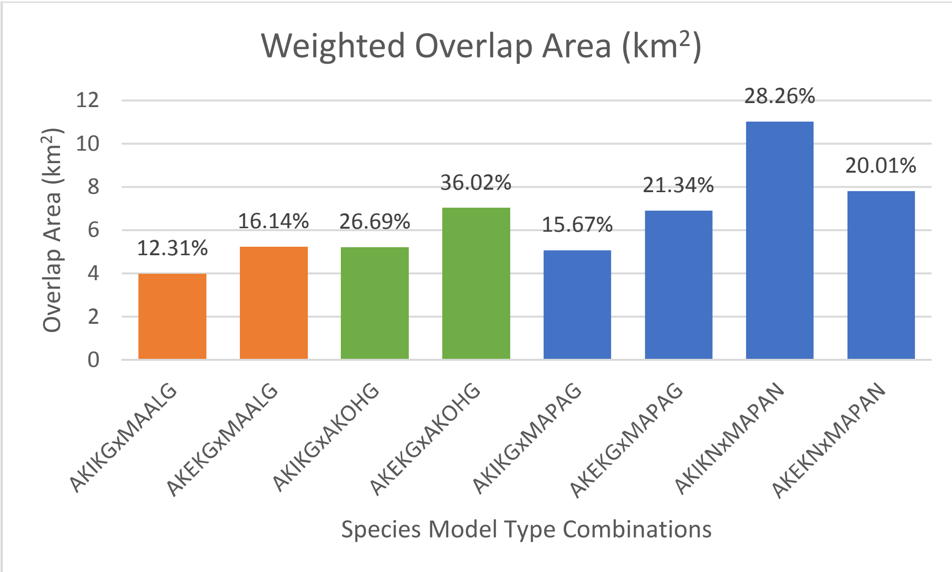


Figure 3. Overlap area (sum of products of the pared pixel-level MaxEnt suitability predications for overlapping pixels) for Kauai species and the Maui species, for each available response type (N=nesting habitat, G=general use habitat), across the Maui area of interest. The percentage of the overlap relative to the habitat area of the Maui species is given for each bar.

4. DISCUSSION

4.1. Kauai Species Nesting Habitat on Maui

The high AUC scores for the Kauai species models with the reduced number of lidar-derived variables suggests a high level of transferability (Randin et al., 2006; Verbruggen et al., 2013). Overall, the areas of highly suitable habitat based on the lidar-derived vegetation structure and topographic metrics line up well with the climatically suitable habitat on East Maui (Figure 4).

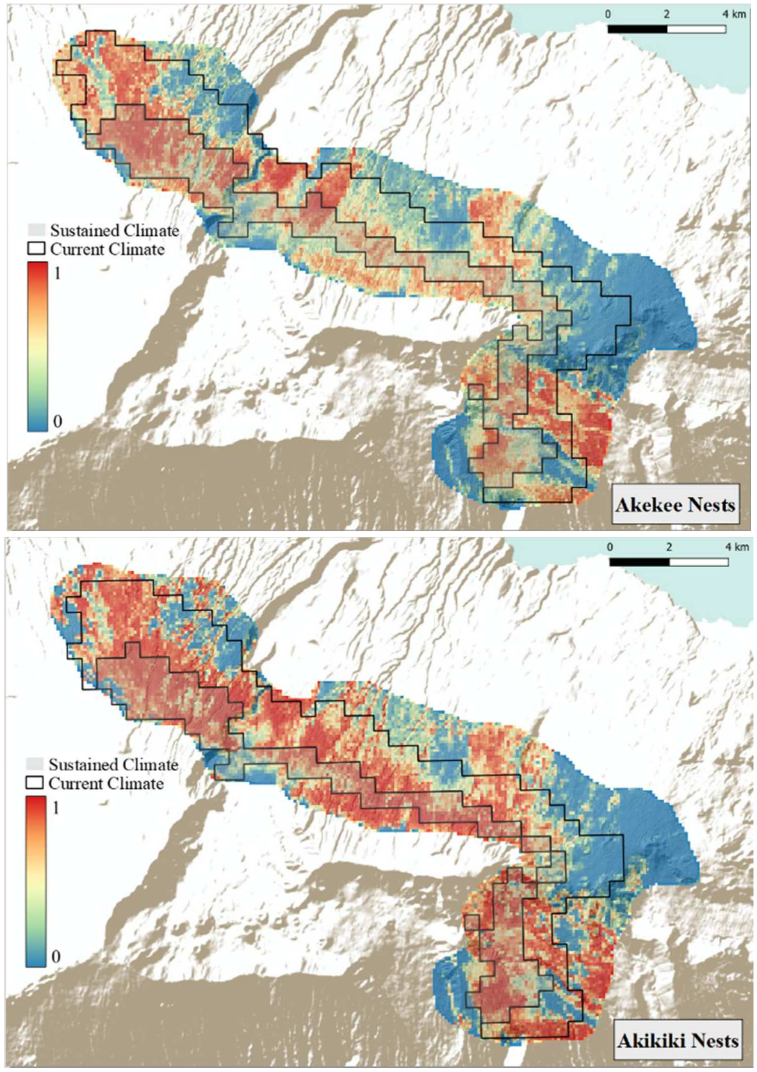


Figure 4. Akikiki and Akekee predicted probability of presence of nesting sites in East Maui overlayed with currently suitable areas (both polygons) and suitable areas under future climate conditions (gray inner polygons).

The results of the Maxent models allow for a more nuanced look at potential release sites within that climatic range for translocation of Akikiki and Akekee. There appears to be more highly suitable nesting habitat for Akikiki compared to Akekee on East Maui (0.54 and 0.43 average suitability respectively) which is apparent also in the nesting range calculations for both species (Table 5). It is difficult to produce measures of accuracy for projected models to novel habitat as there are no known locations for either Kauai species on Maui. However, when comparing the variables of most importance to both species and the distribution of those variables on Maui we can determine if our model results are reasonable (Figure 5).

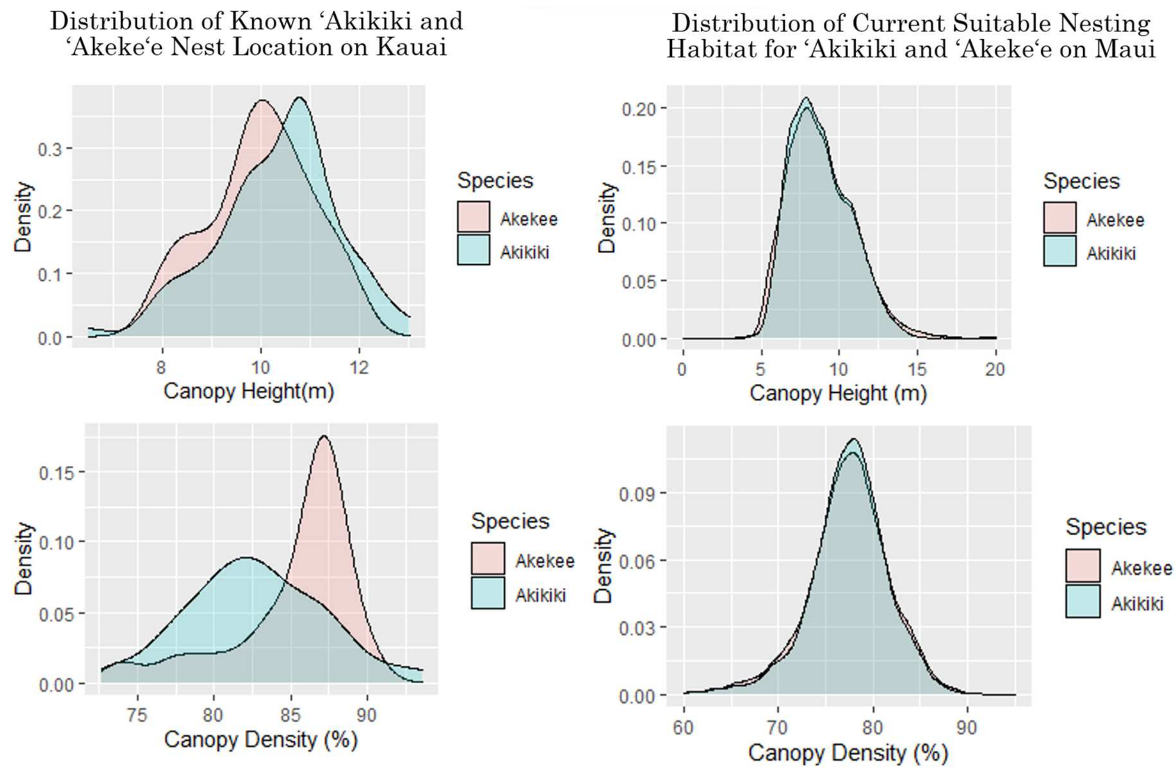


Figure 5. Density plots of canopy height (m) and canopy density (%) of known Akikiki and Akekee nest locations on Kauai (right) and suitable habitat under current climate conditions for both species on Maui (left).

Overall canopy density proved to be the most important driving factor in training gain for both the Kauai species' models for nests and occurrences (Table 4). Additionally, canopy density had consistently the highest percent contribution to all models, followed by relative height 75 and canopy height. This aligns well with habitat suitability modelling of avian species in temperate forests which found that metrics related to canopy cover and canopy height effectively explain species distributions (Bakx et al 2019). When looking at canopy density values in the area on East Maui with currently suitable climatic conditions, they greatly favor Akikiki nesting sites with a distribution centered around 75%. Fricker et al. (2021) found that Akekee prefer denser canopies with less heterogeneity in canopy height. This is reflected in the distribution of canopy density values of known nesting location on Kauai. The narrow distribution of Akekee nesting canopy density values is centered around 87% suggesting that the less dense canopy of East Maui compared to Kauai will be less suitable for this species nesting sites. However, the existence of some highly suitable nesting habitat for Akekee on East Maui can be explained by the shorter canopy and subcanopy height metrics that favor Akekee as Akikiki prefer significantly taller mean canopy heights for nesting (Fricker et al 2021).

4.2. Kauai Species General Use Habitat on Maui

There appears to be more highly suitable general use habitat for Akekee than Akikiki on East Maui suggesting that the birds prefer different habitats for nesting and foraging (Figure 6). Model results show a mean predicted probability of presence of suitable general use habitat for Akikiki of around 0.22 while the Akekee experiences a mean around 0.35. Their maximum predicted probability of presence based on the occurrence models varies only from 0.88 for Akikiki to 0.98 for Akekee. The distributions of canopy density values for known occurrences of Akikiki and Akekee on Kauai are very similar when compared to the values for known nesting sites. Therefore, the effect of that denser canopy preference for Akekee nesting sites doesn’t appear to carry over into their selection of foraging or general use habitat.

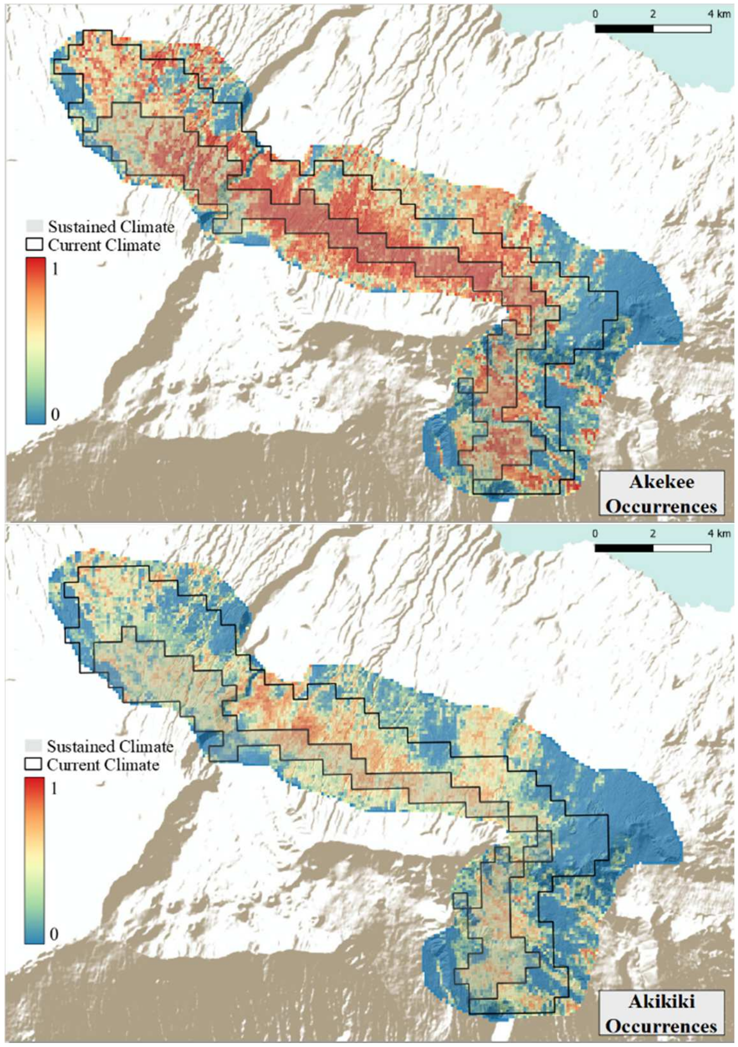


Figure 6. Akikiki and Akekee predicted probability of presence in East Maui overlayed with currently suitable areas (both polygons) and areas suitable under future climate conditions (gray inner polygons only).

Previous research has found that Akikiki's preference for taller canopies and taller understory vegetation structure is prevalent in their foraging behavior as well as nest site selection (Behnke et al. 2016, Fricker et al. 2021). Without the strong influence of canopy density, the consistently shorter vegetation structure metrics (canopy height, relative height 50 and relative height 75) favor suitable general use habitat for Akekee over Akikiki. Fricker et al. (2021) found that Akikiki prefer to nest and forage over steeper slopes than Akekee, which is related to their tendency to nest over streams and forage near those nests whereas Akekee aren't as territorial (Behnke et al. 2016, Fricker et al. 2021). The narrower distribution centered around steeper slopes of East Maui when compared to Kauai values does therefore favor Akekee general use habitat over Akikiki.

4.3. Nesting vs General Use Habitat Models

We found it important to separately analyze the nesting and general use habitat of these birds as they are rare and not much is known of their natural history. Differences in preferences for nesting and general use/foraging habitat could give us insights into the ecological niches filled by these bird species in high-elevation ohia-dominant wet forests. Additionally, the methods for data collection are slightly different for nests than with occurrences, with nest locations generally being more spatially accurate. Previous research has found that honeycreepers like Akikiki and Akekee defend what is called Type B territories (Ralph and Fancy 1994, VanderWerf and Roberts 2008, Hammond et al. 2015). This means that the two species will likely defend a small nesting territory and will not defend foraging territory, leading to differing spatial needs between suitable nesting habitat and suitable general-use habitat for the translocation of these species.

4.4. Competition Potential

An important factor in determining translocation success is estimating the potential for competition between translocated species and species already present in the novel habitat (Wolf et al. 1997). However, it is important to note that Maui used to support much higher densities and diversity of species of native forest birds and the potential translocation of Akikiki and Akekee would be in such low numbers (~40 individuals) that competition will likely not be a factor (Mounce et al. 2018). The weighted overlap area was moderate between all the three Maui species and the two Kauai species (Figure 4). While competition will likely not affect Akikiki and Akekee success on East Maui, one note of concern for the translocation of the Akekee to Maui is that the Maui Akepa (*Loxops ochraceus*) a member of the same genus as the Akekee, went extinct in 1988 (Judge et al. 2019, Paxton et al 2018). Further investigation into the cause of the Akepa extinction on Maui is essential in order to rectify the potential threat to translocated Akekee individuals.

To better understand the intricacies of the relationships between the Maui and Kauai species nesting and general use habitat we ran a Spearman rank correlation of all Maxent model outputs (Table 9). The highest levels of correlation occur amongst the three Maui species and amongst the two Kauai species model outputs. Akohekohe had overall lower correlations to Kauai species nesting and general use habitat which is to be expected because of their unique foraging behavior as the only nectivore in this group of species (Becker et al 2010, Fancy & Ralph 1998). While the weighted overlap between Akikiki and Maui Alauahio is low, they do experience the highest correlation coefficients between Kauai and Maui species (0.33 for general use habitat and 0.42 for Akikiki nesting habitat). This aligns with our predictions as Akikiki and Maui Alauhio exhibit similar foraging behavior (Vetter et al. 2012). Akekee nesting and general use model results correlated the strongest with the Kiwikui nesting model results of all the Maui species. This aligns with our predictions and prior knowledge of both species as they have similar foraging behavior centered around the use of their unique beaks (Vetter et al. 2012). However, it is surprising that the Kiwikui model results were most highly correlated to Akikiki model results. Overall, the correlations between the Maui species and Kauai species are rather low with a maximum correlation of 0.42 and a mean correlation of 0.20. This suggests that competition between Maui and Kauai birds both in foraging and nesting habitat is likely to be low and not a major concern for the translocation of the species to East Maui.

Table 9. Correlation matrix of each mix of species and response type (N=nesting habitat, G=general use habitat) of MaxEnt modelled suitability applied to the Maui area of interest.

	AKOH-G	MAAL-G	MAPA-N	MAPA-G	AKEK-G	AKEK-N	AKIK-G	AKIK-N
AKOH-G	1.00	0.97	0.86	0.93	0.11	0.09	0.21	0.27
MAAL-G	0.97	1.00	0.87	0.92	0.11	0.09	0.20	0.26
MAPA-N	0.86	0.87	1.00	0.90	0.25	0.28	0.33	0.42
MAPA-G	0.93	0.92	0.90	1.00	0.07	0.09	0.18	0.25
AKEK-G	0.11	0.11	0.25	0.07	1.00	0.74	0.80	0.66
AKEK-N	0.09	0.09	0.28	0.09	0.74	1.00	0.67	0.74
AKIK-G	0.21	0.20	0.33	0.18	0.80	0.67	1.00	0.79
AKIK-N	0.27	0.26	0.42	0.25	0.66	0.74	0.79	1.00

4.5. Uncertainty and Limitations

Our models properly address the major sources of uncertainty in habitat suitability modeling of comprehensiveness and quality of presence data, model domain and variable collinearity (Watling et al. 2015). A systematic study of habitat suitability models found that algorithm choice contributes the most to model uncertainty, strongly suggesting the use of multiple algorithms. However, of the three algorithms studied (Maxent, generalized linear model, and random forest) Maxent performed the best with consistently higher AUC scores than comparable model algorithms (Watling et al. 2015).

There may be a certain level of uncertainty associated with the interpretation of these model results due to the exclusion of elevation and climatic variables. However, this uncertainty is addressed using previously developed climate models for Akikiki and Akekee across the Hawaiian Islands. Fortini et al (2017) used an ensemble of SDM model algorithms including Maxent and generalized boosted models. The four selected climate predicters were mean annual temperature, temperature annual range, mean annual precipitation and precipitation seasonality all modelled at the 250 m resolution. These simple models were highly transferable, avoided complex response curves and therefore overfitting, and showed good fit. Using the results of two separate models with reduced environmental variables (4 climate variables and 5 vegetation structure variables), reduces the likelihood of overfitting the models and therefore makes them more transferable (Yates et al 2018). There is also the issue of scale, a large factor in model accuracy for rare species. While there is no one correct scale for describing species distributions, habitat suitability is related to range of environmental variables that occur at different spatial scales (Draper et al 2019, Pearson & Dawson 2003, Store & Jokimaki 2003, Wiens 1989). Here we can describe finer scale vegetation structure and topographic metrics that influence habitat suitability and microclimates while at the same time considering the coarser scale climate factors that additionally effect habitat suitability in differing ways. We created maps of uncertainty for the Kauai species models transferred to Maui by mapping standard deviation among the 100 model replicates (Figure 7). Overall, standard deviation is low among model results, with some clusters of moderate uncertainty.

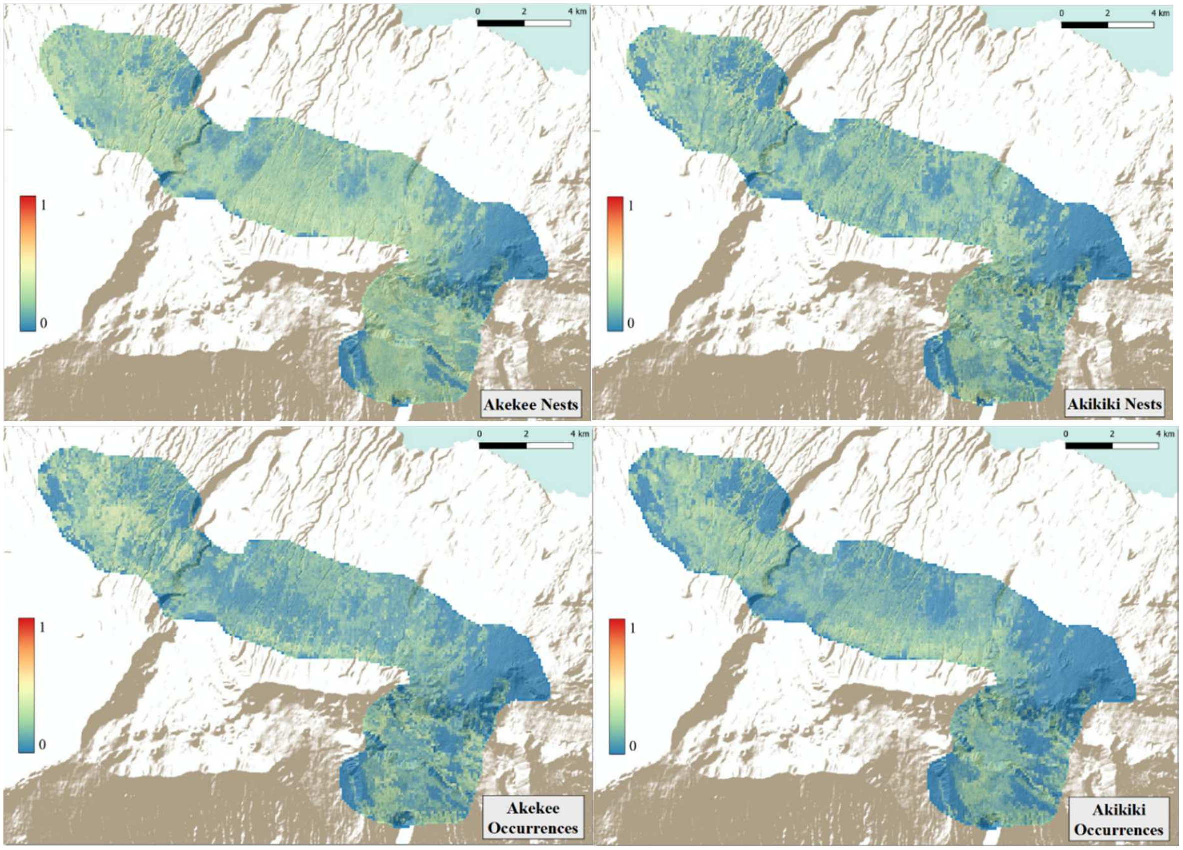


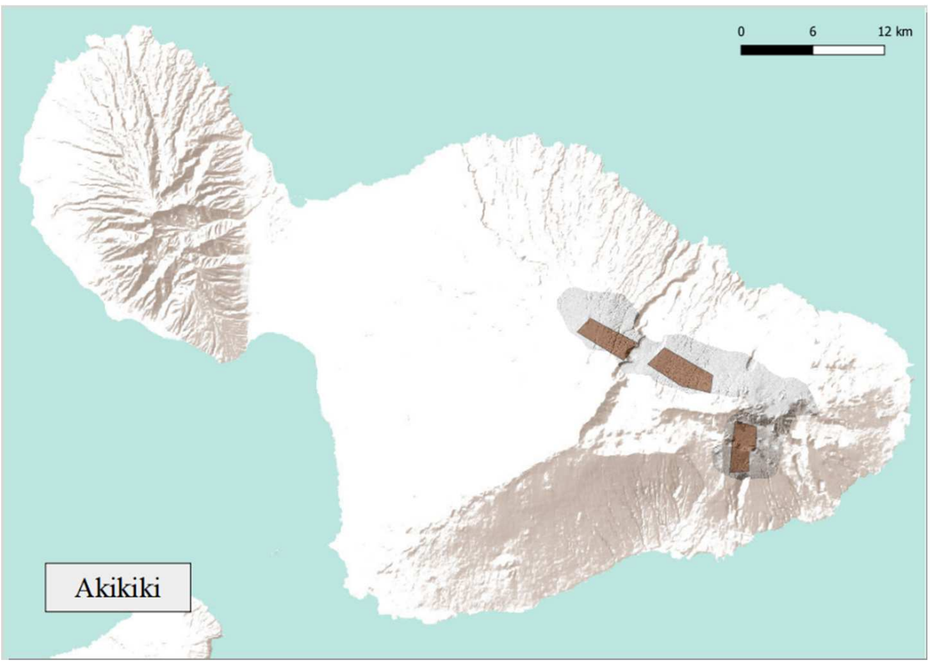
Figure 7. Standard deviation of 100 bootstrapped replicates of nesting and occurrence model outputs for both Kauai species on East Maui.

The lidar data for native forest bird habitat on Kauai was collected with a Riegl LMS-Q560 single channel system that does differ from the GAO system in some meaningful ways that may impact results. First the Kauai lidar was collected from a helicopter at a lower elevation while the GAO system was aboard an airplane. The beam divergence of the two systems is very close but given the higher altitude of the Optech HA500 dual-channel the lasers are likely higher wattage. The higher wattage lasers can therefore penetrate further into the canopy allowing for greater understory detections. This could explain the differences in distribution between the Maui and Kauai relative heights, particularly relative height 25 which is generally shorter for Maui (Figure 3). Additionally, the higher energy beam on the GAO is likely to detect more thin upper branching than the Riegl system. This could explain the generally higher distribution of canopy height on Maui than Kauai. However, it is difficult to determine how much of this difference is due to differences in vegetation structure between the two areas and the differences in the lidar collection systems. There are two properties of the Riegl system that could make up for the beam power issues. First, the Riegl system was flown at a much lower altitude (500 m vs 2000 m) this decreases beam size when it enters the canopy by 4x, which would react to fewer leaves/branches on the path to the ground. Conversely, the smaller beam size allows for smaller branches to deflect the entire beam. Second, the Riegl system uses a waveform recorder and discreate point returns are computed from these waveforms in post-processing, allowing potentially many more detections per pulse than the 4ppm max in the GAO system. Overall, the Riegl system is flown lower to achieve the same level of ground detection as the higher energy beam on the GAO system. While this results in a higher point density, there may be better detection of lower canopy points in the GAO system. The difference in relative height distributions that were eliminated from the analysis are likely partially due to these system differences.

4.6. Implications for Management

Minimum training presence thresholds from Kauai model results led to a greater nesting and general use ranges for both Akikiki and Akekee on Maui under current climate conditions. The only comparable areas between the islands under current climate conditions are Akekee general use ranges with 58 km^2 on East Maui and 57.5 km^2 on Kauai. However, translocation is a complicated and expensive bureaucratic process that can take several years (Dade et al. 2013). This is also the case for landscape mosquito control on Kauai (Lapointe et al 2012). Therefore, to recommend translocation we need areas that are suitable under future climate conditions to allow for the time it would take to make Kauai mosquito free for potential re-introduction. When looking at ranges under future climate conditions, our results lead to a reduction in ranges for both Akikiki and Akekee general use habitat. Akikiki experience a nesting range 10 km^2 higher on Maui under future climate conditions compared to their current range on Kauai. It is also important to note that Fortini et al (2017) found a 100% loss of climatically suitable habitat on Kauai by 2080 for both Akikiki and Akekee under future climate conditions so it may be unfair to compare current Kauai ranges with stable Maui ranges. Given the recent emergency status of Akikiki on Kauai, translocation to Maui may be a viable option to provide stable nesting habitat for this functionally extinct species of honeycreeper (unpublished KFBRP data). Results of these models can lead to the determination of appropriate release locations for translocation by identifying areas of high suitability and low uncertainty. Given the results of both the nesting and occurrence models for Akikiki, we selected three preliminary release sites for Akikiki on East Maui where future research can be focused to determine their viability (Figure 8). These sites were selected by adding nest and occurrence suitability, subtracting combined uncertainty, and selecting areas suitable under future climate conditions that were large enough to support at least 30 Akikiki individuals (6.9 km^2). This was based on Hammond et al. (2015) which observed nearest neighbor Akikiki nest distance to be ~268 m. However, the lack of stable habitat on East Maui for Akekee and the relatively small ranges of Maui species truly emphasizes the dire need for mosquito control across the Hawaiian Islands. Additionally, disease prevalence and distribution are not directly modelled by this study. While climate and elevation are reasonable proxies for mosquito and avian malaria distribution, they are not direct variables included in this analysis. Another factor to consider for translocation is the fact that Akikiki and Akekee raised in captivity have been reared in a sterile environment different from that of the Alakai plateau and East Maui. More research into gut microbiota, foraging ability, and predator avoidance of the captively bred individuals needs to be conducted to determine the viability of translocation (Berry et al. 2019, Costantini et al 2021).

Figure 8. Sites of high habitat suitability and low uncertainty for Akikiki indicated with brown polygons over the lidar extent on East Maui.



4.7. Future Research

Fortini et al. (2017) found areas of suitable future climate on both Maui and the island of Hawaii for Akikiki and Akekee. With the acquisition of high-resolution lidar data for Big Island, this work could be easily replicated for the analysis of potential translocation areas on Big Island. The Maui Forest Bird Recovery Project has also put great effort into habitat restoration on the leeward side of Haleakala, and lidar collection in that area could expand the maxent model results to include more suitable habitat on the island for the three endemic species. Additional data regarding the phenology and floristic composition of these two montane wet forest in

Hawaii could be helpful in assessing the viability of translocation as a management solution (Burger et al 2013). Given the high level of fit and transferability of these models, similar metrics could be used for analysis of translocation potential for other rare and endangered avian species to novel climatic and spatial habitats.

5. CONCLUSIONS

Simplification of lidar-derived habitat suitability models through the reduction of correlated variables led to models with good fit and high transferability. Structurally suitable habitat derived from lidar-based models and climatically suitable habitat for Kauai species on Maui had high levels of overlap, allowing for analysis of suitable habitat at two different scales. Canopy density was consistently the most important metric, emphasizing the importance of forest management and restoration in this area of Maui. The reduced canopy density on Maui compared to Kauai favors Akikiki nesting habitat while the shorter vegetation structure metrics (canopy height, relative height 50, and relative height 75) favor Akekee general use habitat. There is more highly suitable nesting habitat for Akikiki than Akekee on Maui but the reverse is true for general use habitat, suggesting that the birds prefer different habitats for nesting and foraging. Correlations between suitable habitat for endemic Maui species and the two Kauai species were low, suggesting a low likelihood of niche competition as a significant threat from translocation. Current climate conditions on Kauai provide higher ranges for both species when compared to stable ranges on Maui under future climate conditions, except for Akikiki nesting habitat. Given their emergency status and increased potential nesting range, translocation of Akikiki individuals to East Maui is a viable option. The results of these models can be used to inform potential release sites for said translocation. For Akekee it may be more dangerous, given the reduced nesting habitat on Maui and the past extinction of similar species. The methodology used in this study can be replicated for future translocation viability analysis in the Hawaiian Islands and beyond.

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