Identifying Priority Sites for Mosquito Control to Protect Maui's Endemic Forest Birds

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Abstract

Infectious disease is a major emerging cause of species decline as rising global temperatures drive mosquito vectors into cooler, higher elevation habitats that were previously disease-free. The effects of these range shifts are particularly concerning for endemic forest birds on the island of Maui, Hawai'i, where seldom habitat remains at these altitudes. Fortunately, preliminary applications of *BTi* larvicide have been successful in killing mosquito larvae within treatment areas, and plans to continue application along with other forms of mosquito control are being implemented. Due to the novelty of its use in conservation, this study identifies the suitability of sites for the aerial application of *BTi* to control mosquito populations and reduce the transmission of avian malaria among Maui's endemic forest birds. Spatial data on mosquito larval densities, bird populations, and environmental conditions are analyzed to create predictions of where *BTi* aerial application might be most effective, with areas managed by The Nature Conservancy and the federal and state government scoring particularly high in suitability. The findings of this study are intended for academic purposes and must be reviewed by experts in the field if used to inform management decisions.

Introduction

The spread of infectious diseases among wildlife is a major emerging driver of species decline (Samuel et al., 2015). While habitat loss and degradation pose some of the most significant threats to wildlife, their effects are amplified in presence of infectious diseases that contribute to further population reductions (McCallum et al., 2024). This makes island species, which are often already limited in population and habitat size, especially vulnerable to disease transmission (National Academies Press (US), 1995). Many birds on the Hawaiian islands, in particular, evolved in the absence of diseases common on continents, causing them to be more susceptible to newly introduced diseases (Paez et al., 2022).

Avian malaria (*Plasmodium relictum*) is a deadly infectious disease transmitted between birds via mosquitoes (Samuel et al., 2015). Although high-altitude forests have provided some birds with refuge because their cool temperatures are unfavorable for mosquito reproduction, warming climates have reduced the size of these areas and driven them to progressively higher elevations (Paez et al., 2022). This trend poses a serious threat to endemic forest birds in the Hawaiian islands, where even the highest-altitude forests may soon become warm enough for mosquito survival and reproduction (Paxton et al., 2022).

Protecting endemic Hawaiian forest birds from extinction is important for several reasons; many of which are involved in the ecosystem services they provide. As some of the only native vertebrates that feed on the fruit and nectar of native plants, these birds play a key role in seed dispersal and pollination (Barton et al., 2021). Furthermore, native birds are incredibly significant in Hawaiian religion and culture. They have strong connections to the Hawaiian gods, deities, and familial spirits, with some believed to take them on as a physical form (Maui Forest Bird Recovery Project, 2022). Ancient Hawaiian nobility also wore adornments such as *ʻahuʻula* (feathered cloaks) made out of feathers that had been carefully harvested from these birds (Paxton et al., 2022).

Endemic Hawaiian forest birds will likely go extinct within the next 10 years if rapid and effective action is not taken (Judge et al., 2021). Although captive care and translocation may provide short-term protection against extinction, robust mosquito control measures must be implemented if these birds are to persist in the wild (Paxton et al., 2022).

To reduce the transmission of avian malaria and the risk of extinction for endemic Hawaiian forest birds, conservation groups such as the Kauaʻi and Maui Forest Bird Recovery Projects have recently begun using *Wolbachia* Incompatible Insect Technique (IIT) and *Bacillus thuringiensis israelensis* (*BTi*) larvicide to target mosquitos at both the adult and larval life stages (Department of Land and Natural Resources et al., 2024).

Wolbachia is a naturally occurring bacterium found in approximately 60% of insects. While the bacterium is generally harmless to its host, it prevents eggs containing incompatible strains of *Wolbachia* from hatching. Therefore, only pairs of mosquitoes with the same strain of *Wolbachia* can mate to produce viable offspring. When mosquitoes with incompatible strains of *Wolbachia* mate, the eggs they produce will be infertile (Thomas, 2024).

Wolbachia Incompatible Insect Technique (IIT) takes advantage of this unique reproductive trait by purposefully introducing male mosquitoes with incompatible strains of *Wolbachia* into an existing population (Department of Land and Natural Resources et al., 2024). Unlike females, male mosquitoes do not bite, so they do not pose a risk of transmitting disease (Thomas, 2024). Therefore, by flooding sites with approximately ten *Wolbachia* incompatible males for every one compatible male in the area, the likelihood that a female will mate with an incompatible male and produce infertile eggs drastically increases (Department of Land and Natural Resources et al., 2024).

This technique has already been successful in reducing the spread of mosquito-borne diseases such as Zika and dengue that threaten human health worldwide. However, a recent trial on East Maui was the first known use of IIT for wildlife conservation. Since November 2023, hundreds of thousands of male mosquitoes with incompatible *Wolbachia* strains have been released in established treatment areas on a regular basis (Thomas, 2024).

Bacillus thuringiensis israelensis (*BTi*) is another naturally occurring bacterium often used for mosquito control. Unlike *Wolbachia*, however, *BTi* targets its host at the larval stage (Department of Land and Natural Resources et al., 2024). When mosquito larvae ingest the bacterium, the toxins within it bind to a specific site only found in larval midgut cells, causing the cells to lyse and the larvae to die shortly after (Lacey, 2007). Because of this precise mechanism by which it kills its host, *BTi* does not affect non-target organisms and is regarded as a safe and effective method of mosquito control (Kaua'i Forest Bird Recovery Project & DLNR Forestry & Wildlife, 2023).

Like *Wolbachia* IIT, *BTi* has been used to reduce the spread of mosquitoes that transmit diseases threatening human health worldwide (US EPA, 2024). However, a 2023 pilot study in which *BTi* was aerially applied over hundreds of acres on Kaua'i and Maui was its first known use for conservation at such a large scale (Department of Land and Natural Resources et al., 2024). The treatment areas in this study had higher larval mortality rates than the control areas, with significant differences even in sites where water pools were partially sheltered by vegetation (Navarrete et al., 2024). Therefore, although studies are still sparse, aerial application of *BTi* could be an effective method to reduce mosquito populations in Hawaiian forests.

As a result of the success in pilot studies as well as the high host specificity and safety of *BTi,* efforts to continue applying the product are underway to control and prevent further spread of avian malaria among endemic birds in Hawai'i (Department of Land and Natural Resources et al., 2024). Present and future conservation strategies involve distributing the bacterium by helicopter over treatment areas in the form of an aerial spray (Green & Chang, 2024).

Due to the aforementioned novelty of *BTi* usage for conservation, this study incorporates various factors to identify priority sites for the aerial application of *BTi* to reduce mosquito populations in Maui, Hawai'i. Data analysis on mosquito larval densities, weather, slope, and habitat type are used to create spatially explicit recommendations for areas in which *BTi* should be implemented. Using this approach, this study identifies which factors are important in determining site suitability, where endemic Hawaiian forest birds are most likely to be found, and where *BTi* should be aerially applied to most effectively control mosquito populations and protect endemic forest birds on Maui.

Methods

Study Site – This study focuses on the island of Maui, Hawai'i, one of the eight main islands in the Hawaiian archipelago (Barton et al., 2021). Located in a highly remote region of the Pacific Ocean, it is considered a biodiversity hotspot and home to many endemic species (Madson et al., 2022). Maui contains a variety of distinct habitats including coastal wetlands, montane forests, and subalpine to alpine communities, with native dominated habitats comprising approximately one third of the island (H. T. Harvey & Associates [Ecological Consultants], 2015, p. 6–58). Birds such as the Maui 'alauahio (*Paroreomyza montana*), 'ākohekohe (*Palmeria dolei*), and kiwikiu (*Pseudonestor xanthophrys*) currently reside in high elevation native forests on east Maui, where temperatures are too cold for disease transmission via mosquitoes (Paxton et al., 2022).

Workflow – To address my research questions and create a suitability map of Maui for areas in which *BTi* should be implemented to control mosquitoes and protect endemic forest birds, I adapted a workflow recommended by Esri, the owner of the mapping software "ArcGIS Pro." This process involved the following steps: (1) obtain and assign scores to criteria data, (2) standardize scores using a common scale, (3) weight criteria according to relative importance, and (4) locate areas with the highest suitability scores (Esri, 2024b).

Step 1: Obtain and assign scores to criteria data.

Four main criteria were identified to be highly influential in the suitability of sites for aerial *BTi* application: mosquito larval density projections (MLDP), weather conditions, slope, and habitat type (Dyson, 2024 & Table 1). For data that varied seasonally, only values from August 2023 were used to ensure the final map represented site characteristics as accurately as possible. August was chosen due to the high presence of mosquito larvae during this month (Spafford, 2018). All data were projected onto the same coordinate system, "NAD 1983 HARN UTM Zone 4N," and cell sizes as well as the snap raster were set to 40 x 40 to match the MLDP data (Esri 2024a).

Mosquito Larval Density Projections (MLDP) – MLDP represented the expected densities of mosquito larvae across the island of Maui in August (Vorsino, 2024). These projections were modeled based on research from Kauaʻi because there was only very limited data from Maui. Areas with the highest MDLP received the highest suitability scores for *BTi* application (Dyson, 2024).

Weather Conditions – Weather conditions were represented by monthly precipitation and wind speeds from August 2023 (*Historical Rainfall*, 2023 & AWS Truewind, LLC, 2013).

Precipitation – The precipitation layer was represented by monthly rainfall values from August 2023 (*Historical Rainfall*, 2023). There is no standardized definition for monthly rainfall in terms of its suitability for helicopter operations, so ArcGIS's "natural breaks" were used to classify the data into three groups (Esri, 2024a). Areas with heavy rainfall were considered to be least suitable for helicopter operations, areas with light to moderate rainfall were considered to be intermediate in suitability, and areas with very little to no rainfall were considered to be most suitable (Zhao et al., 2024, Unpublished manuscript).

Wind Speed – Average wind speed as calculated from 366 randomly selected dates within 15 years was used to represent wind speed at altitudes of 30 meters above the ground (AWS Truewind, LLC, 2013). Data for this altitude were selected following manufacturer recommendations for aerial applications of the product at approximately 100 ft above the ground (Valent BioSciences Corporation, n.d.) and at wind speeds of 12 mph or less (Zhao et al., 2024, Unpublished manuscript). The "nibble" spatial analyst tool was used to replace the values of cells without data with that of their nearest neighbor (Esri, 2024c).

Slope – Elevation data from the 2013 "Living Atlas" was converted to slope using geoprocessing tools. This layer represented the slope as one of three classes: flat (< 5 degrees), moderate (5-15 degrees), steep (>15 degrees), where flat areas were considered most favorable for consistent application of product via aerial spraying by helicopter (Dyson, 2023, Unpublished manuscript).

Habitat Type – Habitat type included both native bird range and native forest habitat. The native bird range layer reflected the range of the Maui ʻalauahio population in 2023, while the native forest habitat layer reflected all areas dominated by native vegetation.

Native Bird Range – Native bird range was determined using the range of Maui ʻalauahio, whose range also encompassed that of the ʻākohekohe and kiwikiu populations in 2023 (Maui Forest Bird Recovery Project, Unpublished data).

Native Forest Habitat – Native forest habitat was determined an important factor in site suitability, with areas dominated by native vegetation classified as most suitable for native birds (U.S. Geological Survey & Jacobi, 2015).

Step 2: Standardize scores using a common scale.

Values for the suitability score of each criteria were normalized so they could be compared with one another based on a common scale. The scores for each criteria were normalized to values between 0 and 1 using the minimum-maximum method of standardization, which took the input values and placed them on a scale of 0 to 1, with 0 representing the lowest suitability and 1 representing the highest suitability levels (Esri, 2024a).

Step 3: Weight criteria according to relative importance.

Criteria were assigned weights and sent through the "weighted sum" geoprocessing tool using their normalized values to produce final suitability scores. These weights were determined with the assistance of input from expert MFBRP staff to reflect their relative importance in determining site suitability for *BTi* application (Esri, 2024a & Table 1).

***Table 1 (Below)**: Criteria, data sources, and relative weights. Main criteria are indicated in bold.*

Criteria	Data Source	Weight
Mosquito Larval Density Projections (MLDP)	**Mosquito Larval Density Projections: August Median CI Projections (Vorsino, 2024)**	**0.30**
Weather (Precipitation & Wind Speed)	**Precipitation & Wind Speed**	**0.20**
Precipitation	August Monthly Rainfall 2023 (Hawaiʻi Climate Data Portal, 2023)	0.10
Wind Speed	Wind Speed 30m (AWS Truewind, LLC, 2013)	0.10
Slope	**Terrain: Slope Map (Living Atlas, 2013)**	**0.15**
Habitat Type (Native Bird Range and Native Forest Habitat)	**Native Bird Range & Native Forest Habitat**	**0.35**
Native Bird Range	Maui ʻalauahio Range 2023 (Maui Forest Bird Recovery Project, Unpublished data)	0.20
Native Forest Habitat	Carbon Assessment of Hawaii - Habitat Status (U.S. Geological Survey & Jacobi, 2015)	0.15

Step 4: Locate areas with the highest suitability scores.

Map symbology was set to a color gradient from red to teal to identify areas most suitable for the aerial application of *BTi* (Esri, 2024a). Red was used to represent areas with the lowest suitability, whereas teal was used to represent areas with the highest suitability. Beige and other transitional colors were used to further classify areas with intermediate suitability. General place names were added for localization (U.S. Census Bureau, 2021), and outlines of government-owned lands and reserves were added for specific identification of high-suitability areas (Division of Forestry and Wildlife, DLNR, 2024).

Results

This study resulted in a suitability map containing spatially explicit recommendations for areas in which the aerial application of *BTi* could be implemented to control mosquitoes and protect endemic forest birds on the island of Maui from avian malaria. Site suitability was determined by mosquito larval density projections (MLDP), precipitation, wind speed, slope, native bird range, and native forest habitat. Each of these criteria was weighted by relative importance, with MLDP, native bird range, and native forest habitat considered most important in determining site suitability (Table 1).

The final weighted suitability map of Maui can be seen in Figure 2. Areas with the highest suitability scores are represented in teal, areas with intermediate suitability are represented by beige and other transitional colors, and areas with the lowest suitability are represented in red. Government-managed lands and reserves are outlined in black (Figure 2).

Based solely upon the criteria above, areas with the highest weighted suitability scores for *BTi* aerial application included those managed by The Nature Conservancy, the United States National Park System, as well as various state-managed regions within Upcountry Maui. More specifically, areas within Polipoli, Kula Forest Reserve, The Nature Conservancy Waikamoi Preserve, Ko‘olau Forest Reserve, Hanawi Natural Area, and Haleakalā National Park had some of the highest suitability scores on the island. Small regions within Makawao also scored high in suitability; however, maximum values were not reached in this area. Much of South Maui and shoreline areas in general had low suitability scores (Figure 2).

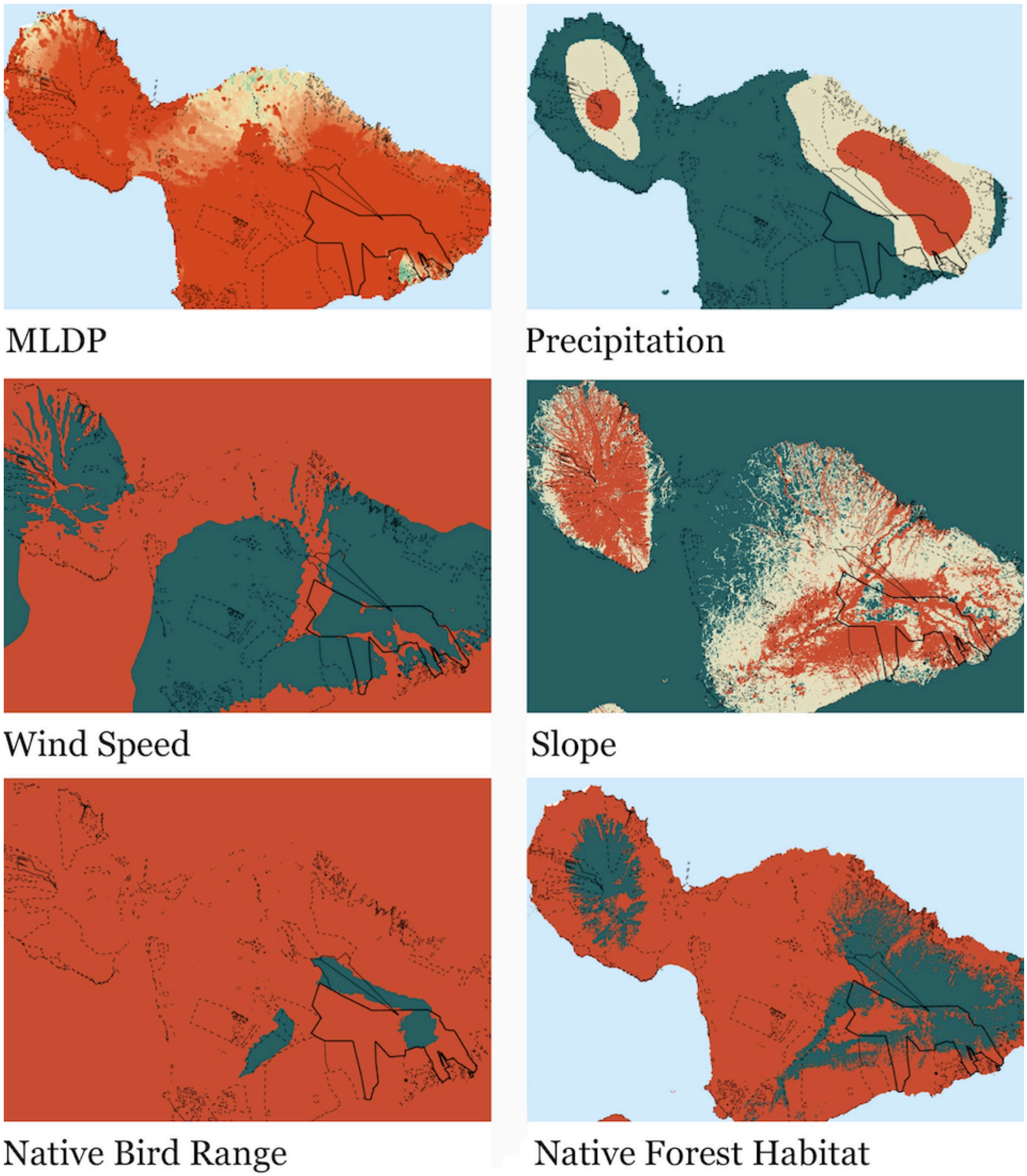

***Figure 1 (Above)**: Representative maps of Maui showing suitability based upon normalized mosquito larval density projections (MLDP), precipitation, wind speed, slope, native bird range, and native forest habitat. Sites are ranked from red to teal, where red is the least suitable and teal the is most suitable for aerial application of* BTi.

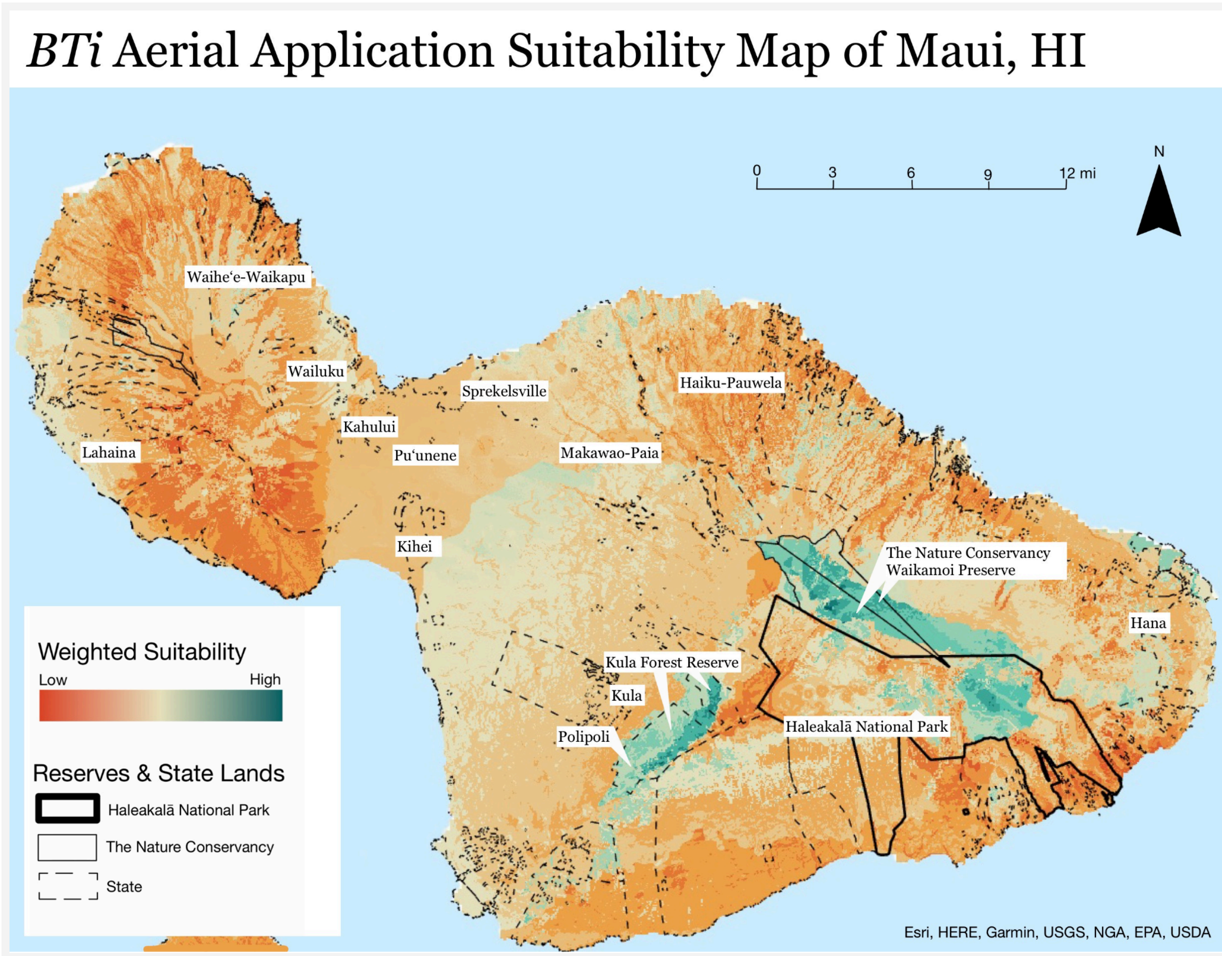

Figure 2 (Above): BTi *aerial application suitability map of Maui, HI. Site suitabilities are represented by weighted suitability scores with values ranging from low to high, with the lowest scoring areas shown in red and the highest scoring areas shown in teal. Lands managed by the United States National Park System are outlined in bold lines, lands managed by The Nature Conservancy are outlined in thin lines, and lands managed by the state are outlined in dashes.*

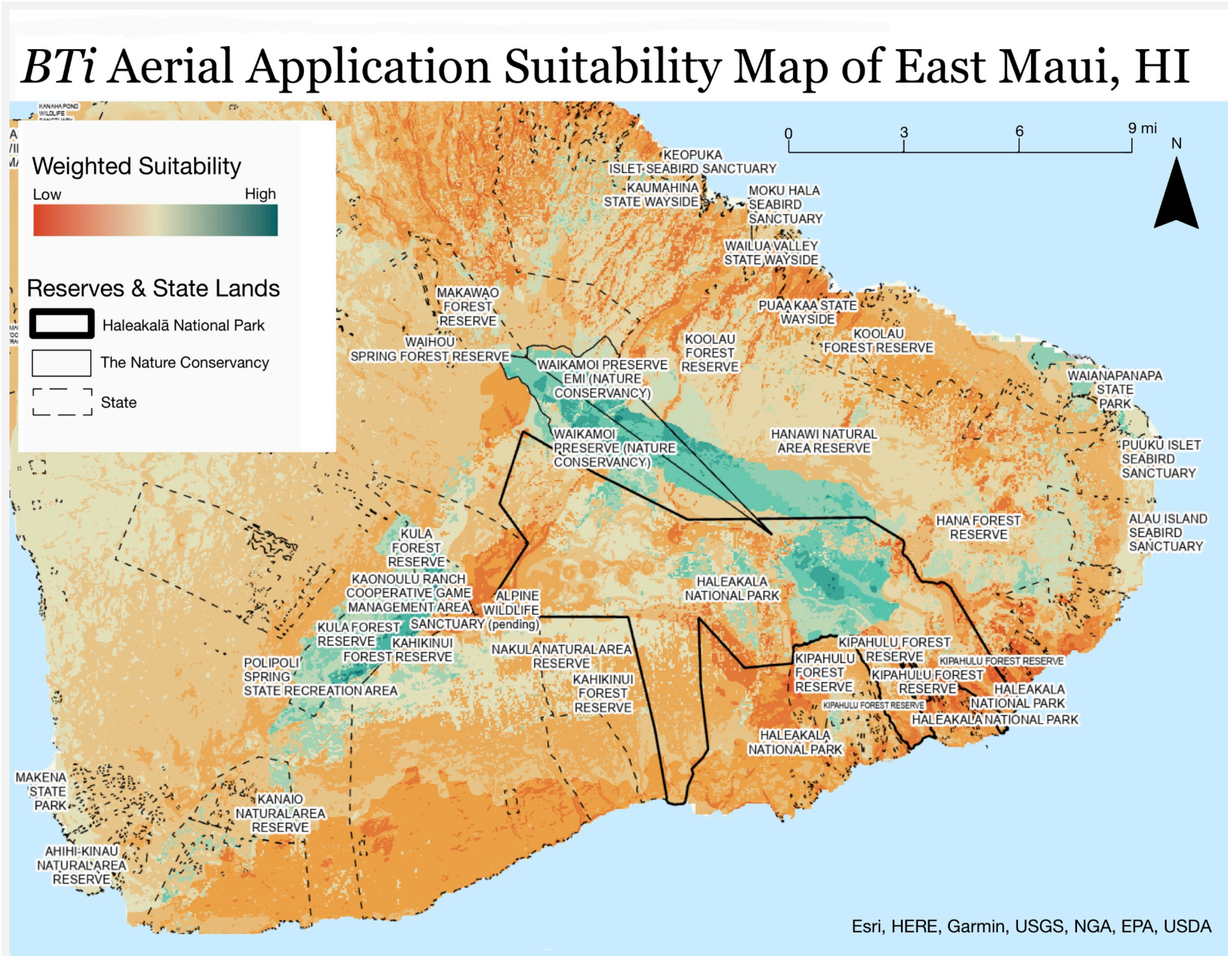

Figure 3 (Above): BTi *Aerial Application Suitability Map of East Maui with place name labels; adapted from map in Figure 2. Areas within Polipoli, Kula Forest Reserve, The Nature Conservancy Waikamoi Preserve, Ko'olau Forest Reserve, Hanawi Natural Area, and Haleakalā National Park had some of the highest suitability scores on the island.*

Discussion & Conclusions

Endemic Hawaiian forest birds may go extinct within the next 10 years due to the spread of avian malaria if rapid and effective action is not taken to reduce mosquito populations (Paxton et al., 2022). In addition to management techniques such as *Wolbachia* Incompatible Insect Technique (IIT), conservation groups have begun controlling mosquito populations by aerially applying *BTi* larvicide to areas of high concern. Because this is its first known use for conservation at such a large scale, few studies exist on site suitability in the Hawaiian islands (Department of Land and Natural Resources et al., 2024).

This study involved the creation of a suitability map that identified the suitability of areas for the aerial application of *BTi* to reduce mosquito populations and protect endemic Hawaiian forest birds on Maui (Figure 2). The final map was created using data on mosquito larval density projections (MLDP), weather conditions, slope, and habitat type, with each layer weighted by its relative importance. MLDP, habitat type, and slope were weighted as the most important factors by recommendation of experts in the field, while weather was weighted lowest in importance because of its high variability.

Mosquito larval density projections were weighted as one of the most important factors in determining site suitability due to the mechanism by which *BTi* works. *BTi* effectively reduces the survival of mosquito larvae, thus reducing the growth of mosquito populations (Navarrete et al., 2024). Even though the MLDP used in this study were created by a professional ecologist, there was very limited data to work with; therefore, these projections should not be treated as absolute. In other words, due to the inherent uncertainty in the current data models, the MLDP should be further refined before deciding where to apply *BTi* (Vorsino, 2024).

Wind speed and precipitation were weighted as some of the least important factors in determining site suitability because of their high variability. A site with generally little to no precipitation, for instance, could receive heavy rainfall during a storm, thus rendering that site unfavorable for *BTi* application that day (Zhao et al., 2024, Unpublished manuscript). This is a noteworthy limitation of the final map that must be considered when applying *BTi* on the island.

Slope was factored into site suitability because of its influence on the consistency of product application. Aerial application of *BTi* via helicopter is most consistent over flat areas and becomes less consistent as slope increases. Therefore, flat regions were considered highly suitable for *BTi* application because they were most likely to receive a consistent application of product, whereas steep regions were considered least suitable due to their predicted inconsistencies in product application (Dyson, 2023). The weight of this criteria should be reconsidered if alternate application methods are used.

The presence of native forest habitat was considered an important factor because this was the main habitat status within the native bird ranges from 2023 (Maui Forest Bird Recovery Project, Unpublished data, & U.S. Geological Survey & Jacobi, 2015). While it is true that native forests dominate much of the current native bird ranges, it is also important to note that correlation does not imply causation. Other factors such as the presence of predators may also influence whether a habitat is suitable for native birds (Mounce et al., 2021). Therefore, although the final map classified areas dominated by native forest habitat as highly suitable for *BTi* application, it is possible confounding factors could prevent native birds from inhabiting those areas even if they were mosquito-free. Future studies should consider this to create more accurate recommendations.

Considering the study criteria, areas managed by the The Nature Conservancy, the United States National Park System, and the state government were determined as some of the most suitable sites for the aerial application of *BTi*. Of these areas, regions within Polipoli, Kula Forest Reserve, Waikamoi Preserve, Koʻolau Forest Reserve, Hanawi Natural Area, and Haleakalā

National Park scored especially high on the suitability scale (Figure 3). High suitability scores strongly reflect the presence of native birds and native forest habitat in these areas (Figure 1), and the fact they are overseen by authoritative agencies is encouraging for conservation work, especially since Haleakalā National Park is federally managed land (Navarrete et al., 2024).

Although many of the areas identified as highly suitable were as expected, there were still limitations to this study that may have caused inaccurate representations. For instance, one major limitation to site suitability score was the influence of weather conditions, which vary daily and must be accounted for at the time of application. Along with variable weather, the lack of consideration for criteria such as buildings, roads, and other infrastructure, as well as predators or invasive species, may have skewed the results to include unfavorable sites (Birds, Not Mosquitoes, 2023). As a result, it would be worth including these factors before making final decisions on where to apply *BTi*. The extent to which these criteria should be weighted could be determined by researchers with more experience on the subject.

In addition to the exclusion of some potentially influential criteria, limited data on mosquito larval densities in Maui made confidence in mosquito larval density projections quite low (Vorsino, 2024). Future analyses that incorporate real-time weather, updated mosquito larval density projections, and various additional criteria could improve spatial recommendations for the aerial application of *BTi*. It could be useful to have a meeting with scientific researchers, island community members, and conservation groups to discuss which of these criteria may influence site suitability most.

Lastly, although the process of creating and refining the map in this study was overseen by researchers and university staff, it is important to note it was ultimately created by an undergraduate student with limited experience. Therefore, it is possible that technical errors may have gone unnoticed. As a result, the weighted suitability map from this study is intended for academic purposes only and must be reviewed, refined, and updated by experts in the field. Further analysis incorporating relevant criteria and addressing study limitations must be done to inform management decisions and reduce the risk of extinction for endemic Hawaiian forest birds.

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