Finding the Breeding Sites of the Coconut Rhinoceros Beetle (*Oryctes rhinoceros*)

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Abstract

The Coconut Rhinoceros Beetle (CRB) threatens Hawaii because it feeds on the coconut palm which is a culturally and economically important plant species. Unfortunately, CRB detections on Oahu continue to increase despite a concentrated eradication effort. This further threatens Oahu's coconut palms and other culturally, environmentally, and/or economically important plant species such as *Colocasia esculenta*, *Pandanus tectorius*, and *Pritchardia spp*. Controlling the spread of CRB on Oahu is important because it will protect areas where CRB has not yet been established. This includes the neighboring Hawaiian Islands and the contiguous United States where the establishment of CRB is estimated to cause millions ($) in damages. Locating breeding sites is prioritized because it prevents future infestation and population growth. This project had three objectives: I) To locate the potential breeding sites of CRB, II) to derive a risk map that delineates possible areas of CRB intensification, and III) to summarize the methods used to produce the risk maps for practical use. Using a geographic information system (GIS), a FISHNET, a net of rectangular cells, suggests that breeding sites were more likely to occur in areas with higher proportions of damaged trees and a higher number of trees. Heat maps were developed to pinpoint the locations of potential breeding sites based on the proximity between damaged trees and the nearest known breeding sites and the number of trap catches. Knowing the likely locations of CRB breeding sites will allow the CRB Response to more easily manage existing populations, especially in areas that have known but unlocatable breeding sites. By focusing on where CRB reproduces, the goal of eradication will be one step closer to realization.

Keywords: Hawaii, GIS, Invasive Species, Risk Map, Palm Trees

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Motivation

Oryctes rhinoceros (*L.*) (Figure 1), the coconut rhinoceros beetle (CRB), threatens coconut palms around the world (Giblin-Davis, 2001). It was first detected on Oahu in December 2013 (McPartlan, 2014) and has since slowly spread throughout the island by flying or typically hitchhiking on green waste transports (HNN 2018). High-risk areas are Central and South Central Oahu. There are currently no established populations on the wetter parts of the island where CRB would become more productive and cause more damage (K. Weiser, personal communication, September 15, 2020). The coconut tree (*Cocos nucifera*) is known as the "tree of life" in many Pacific Island cultures because it has many uses (Chan and Elevitch, 2006). In Native Hawaiian culture, the coconut, or niu, is the kinolau, or embodiment of Ku and was traditionally planted during the birth of a child (Handy et al., 1991). CRB threatens efforts to restore the use of coconuts as a local food source and revitalize cultural practices that use coconuts (Kauanoe, 2021). CRB threatens the 22 endemic Hawaiian species of *Pritchardia* (Loulu) as higher mortality rates for native fan palms than coconut palms have been recorded (CRB Response, 2021). CRB is capable of attacking other culturally and economically valued plants such as *Colocasia esculenta* (kalo), *Pandanus tectorius* (hala) (Figure 2), *Musa sp*. (banana), *Saccharum* (sugar cane), and *Ananas* (pineapple) (Gressitt, 1953).

CRB invasions have devastated palms in other topical areas. Palau experienced a coconut palm mortality rate of 50% with some islands seeing 100% mortality (Gressitt, 1953). CRB is a threat to residential owners and the tourism industries of Pacific Islands like Hawaii and Guam because it attacks palms located on all properties (Campbell 2012, McPartlan, D. 2014). Dead trees are a safety hazard and are pricey to replace. The cost to replace 2,000 palm trees in the tourist district of Tumon, Guam, was estimated to be $2.5 million (Moore, 2009). The coconut palm is Honolulu's third most abundant municipal tree species and provides an average annual benefit of $89.79/tree through benefits such as aesthetic value and energy savings (Vargas et al., 2007). The cost to replace all coconut trees in Honolulu would exceed $2 million (Vargas et al., 2007). CRB caused over $7.6 million in damages to South Pacific Islands in 1969 (Catley, 1969). Established populations can reduce the aesthetic value of tourist attractions and amount of revenue from recreational uses, and create extra costs to remove and replace dying trees (Erikson, 2013; Smith & Moore, 2008). Hawaii would not be able to handle a statewide CRB outbreak. It is still experiencing the effects of the COVID-19 pandemic when its $18 billion tourism industry came to a standstill (Finnerty, 2020). The economic and cultural costs to control CRB and mitigate its effects would be too high.

In Hawaii, CRB is only established in Oahu. It is not established in the continental United States. A USDA pathway analysis found that CRB is more likely to be introduced to North America from Hawaii than from an internationally infested area (Kumar & Bigsby, 2018) where it can establish in 12 conterminous states and cause damages over $900 million annually (Rysin et al., 2018). Aiding in its eradication will protect all at-risk areas from a potential CRB invasion.

Figure 1. An adult Oryctes rhinoceros

Figure 2. Boreholes from CRB on a Pandanus tectorius (Hala)

Background

Invasive species threaten conservation because they cause mass extinctions, alter habitat, and lead to a loss of biodiversity (Daehler et al., 2004). Hawaii is one of the highest housers of invasive species worldwide (Dawson et al., 2017). Introduced species have the potential to become invasive and threaten Hawaii's ecosystems and ecosystem services (Pejchar & Mooney, 2009). For example, *Klambothrips myopori*, an invasive insect that attacks the native *Myoporum sandwicense* (Conant et al., 2009) is found on Hawaii Island and Oahu where it causes galls (King et al., 2012) that results in the dieback of leaves and shoots (Kaufman et al., 2020).

The coconut rhinoceros beetle is native to Southeast Asia (Catley, 1969). Adults are about 3.0 to 6.0 cm (about 2.0 inches) in length, are nocturnal, and have horns (Manjeri et al., 2013) (Figure 1). Breeding sites are typically decomposing green waste, dead palm trees, and soils rich in organic matter. (Manjeri et al., 2013). CRB spends most of its life cycle at its breeding sites (Pallipparambil, 2015). Breeding sites contain beetles at all stages of development because adults leave their breeding sites to feed on palm trees but return to reproduce (Moore, 2019). Females can lay between 70 to 100 eggs in a lifetime (Bedford, 1976). The total lifespan is generally between 4 to 10 months. The damage from adults occurs as a v-shaped cut (Figure 3) or a bore hole (Figure 4) (Bedford, 1980).

The CRB Response is tasked with protecting Hawaii from the CRB. The CRB Response is a coordinated partnership between entities such as the University of Hawaii, the United States Department of Agriculture, and the Hawaii State Department of Agriculture. Over 3,000 pheromone lure traps are used to determine the locations of the highest concentrations of beetles (K. Weiser, personal communication, September 4, 2020). Traps serve as a monitoring tool rather than an active eradication tool. Breeding sites are typically searched for in the vicinity of positive traps. There is some concern that the spatial distribution of the traps is uneven and does not provide good spatial coverage. Breeding sites could be in areas that the response team does not prioritize due to a lack of traps/traps hits and does not have access.

The CRB Response uses an integrated pest management strategy that combines chemical, biological, physical, cultural, and prevention measures (Bedford, 1980). Locating breeding sites remains one of the biggest challenges of the CRB response (Russo, 2019). The canine crew is a recent addition where dogs are trained to identify new breeding sites by scent. This approach was also tried in Guam. Studies in Guam have tried to locate breeding sites by radio-tracking beetles (Moore et al., 2017). Other challenges to the response include controlling the movement of green waste that can transport larvae across the island and convincing businesses to cooperate with mitigation efforts. It is important to control the spread of CRB before the population becomes out of control. In 2015, the devastation in

Guam from Typhoon Dolphin created many potential breeding sites (Moore, 2019). Many were located on inaccessible land (e.g., military land and forests) which helped to facilitate a self-sustaining island-wide outbreak.

Theoretically, CRB can be eradicated by finding and destroying every active breeding site and preventing re-introduction (Smith & Moore, 2008). Sadly, eradication is very hard. The only successful eradication attempt occurred over a 9-year sanitation program on Niuatoputapu Island, Tonga, in 1921 (Bedford, 1980). However, the CRB Response believes that eradication is possible with the combined efforts of public and private stakeholders.

Figure 3. V-shaped cuts on a coconut tree

Figure 4. Bore holes on a palm tree

Objectives

The main objective of this project was to develop methods to locate potential breeding sites using the relationship between known breeding sites and damaged trees along with past trends of CRB population intensification and movement patterns. A series of risk maps were developed and presented to the CRB Response that showed the locations of potential CRB breeding sites. Methods that showed promise in locating potential breeding sites were summarized and handed over to the CRB Response for future reference.

The primary objectives of my capstone project were:

1. To locate the potential breeding sites of CRB
2. To derive a risk map that delineates possible areas of CRB intensification
3. To summarize the methods used to produce the risk maps for practical field use

Approach

This project was performed primarily on a geographic information system (GIS) (ArcGIS Pro 2.7, Esri, Redlands, California, USA, https://www.esri.com).

Study Sites

The study sites consisted of the following management zones as designated by the CRB Response: Pearl City Peninsula (Figure 5), Iroquois - Sugarland (Figure 6), and West Loch - Kapolei (Figure 7). The Pearl City Peninsula Management Zone is in Central Oahu. The Iroquois - Sugarland and West Loch - Kapolei Management Zones are on the ‘Ewa side (i.e., South Central) of Oahu, Hawaii. All Management Zones have agricultural land and residential areas and are adjacent to or contain a golf course and a National Wildlife Refuge. Although trap catches at Pearl City Peninsula and Iroquois - Sugarland have historically been high, the application of landscape-scale palm injections has resulted in lower trap detections for both management zones. The CRB Response is concerned about West Loch because they have found few active breeding sites despite many trap catches and high rates of palm damage.

Figure 5. Pearl City Peninsula Management Zone.

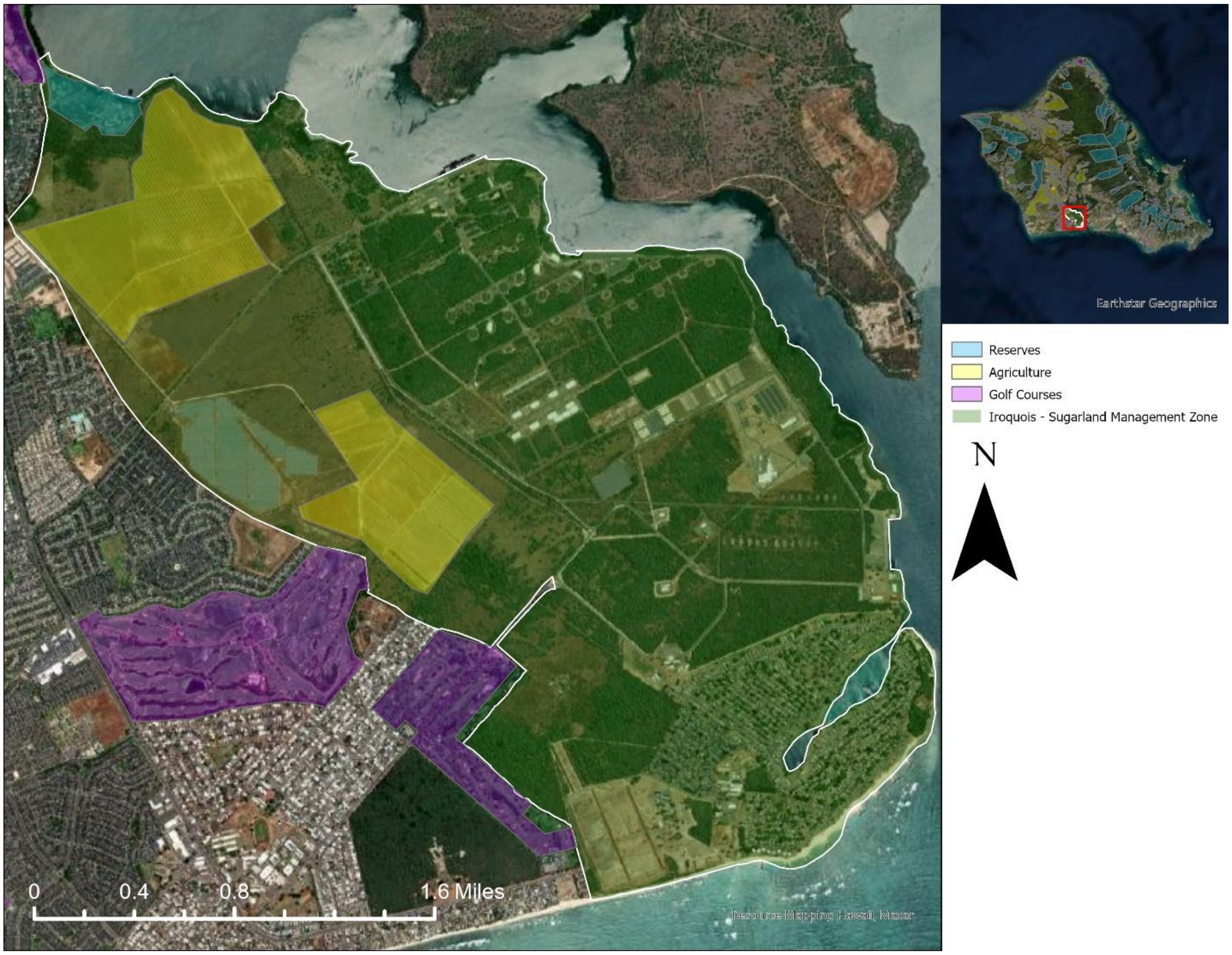

Figure 6. Iroquois - Sugarland Management Zone.

Figure 7. West Loch - Kapolei Management Zone.

Identifying CRB Hosts

I used satellite imagery (Figure 8) provided by ©2020 Maxar (Neigh et al., 2013) to visually locate all palm trees capable of becoming CRB hosts (i.e., plants that CRB feeds on) in the three Management Zones of interest. Trees were digitized as a point-vector shapefile (Figure 9) to create a map of potential hosts. I used the resulting point-vector shapefile to compute a damage ratio and an uncertainty value to normalize for tree density. The CRB Response provided shapefiles that showed the locations of surveyed trees and pesticide-injected trees to increase the accuracy of this process. Sometimes, I used Google Street View to double-check whether a digitized tree was a CRB host (e.g., coconut palm) or a non-CRB host (e.g., Manila palm).

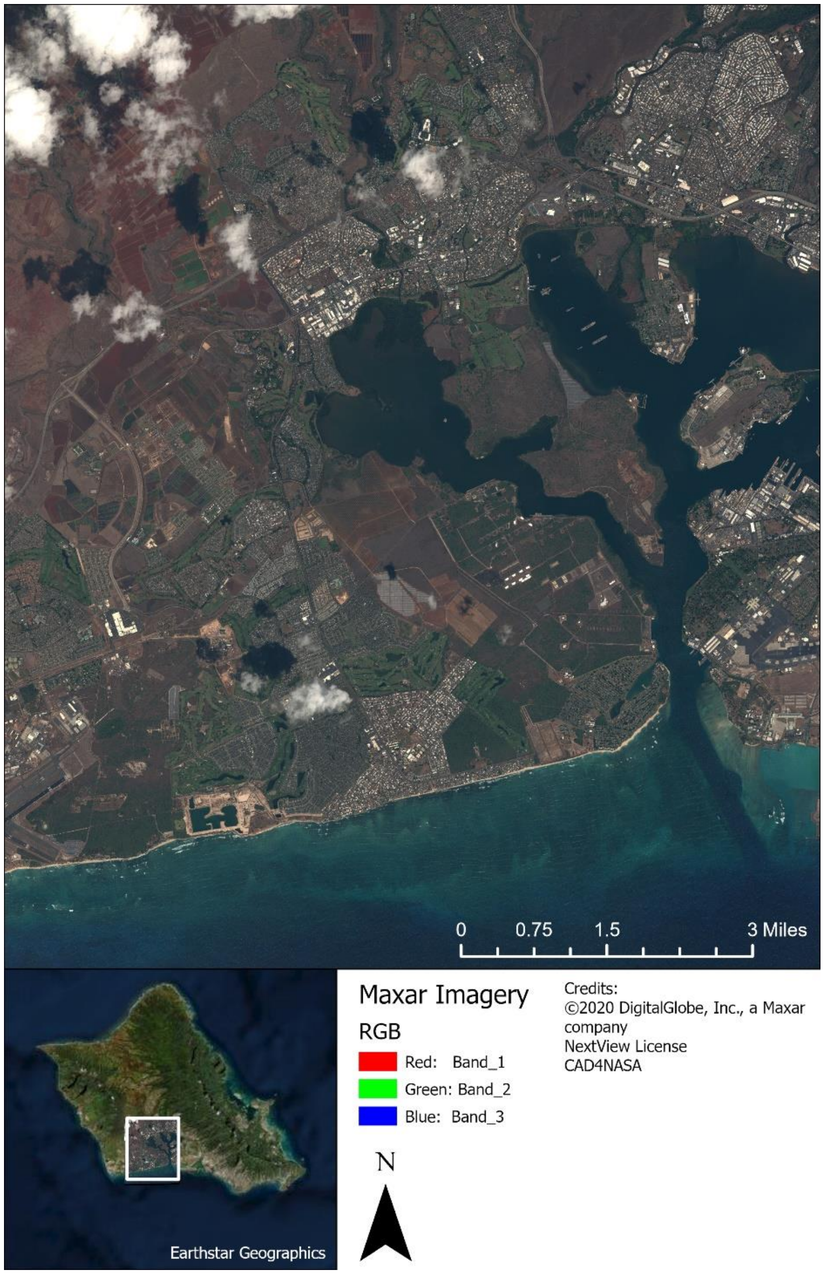

Figure 8. ©2020 Maxar satellite imagery was used as a basemap to identify CRB hosts.

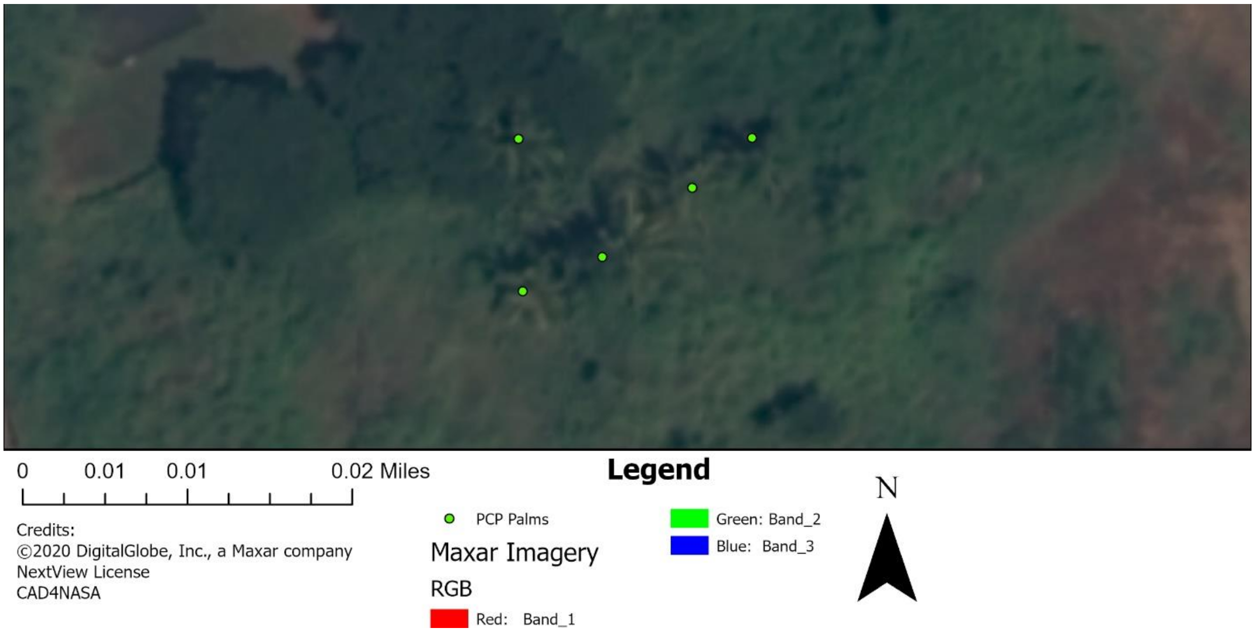

Figure 9. Points placed over palm trees at Pearl City Peninsula.

Tree Density Normalization

Based on observations that areas with higher tree densities appear to have higher rates of damaged trees, the following null hypothesis was created in collaboration with the CRB Response: Every tree has the same likelihood of getting damaged. Therefore, any deviations in the damage rate may indicate proximity to a breeding site. A FISHNET (Figure 10), a net of rectangular cells, was created to normalize tree density by subdividing the CRB Response's "Subgrids" shapefile. Normalization was necessary because areas devoid of palms could still have potential breeding sites. The "Subgrids" were subdivided into fourths to create a "MiniGrids" shapefile. This allowed for a more localized analysis of areas when digitizing palms. Each “MiniGrid” has an average area of 108,871 ft^2 or 10,114 m^2. I used ‘Spatial Join,’ a GIS tool that “joins the attributes from one feature to another based on the spatial relationship (Spatial Join Analysis),” to attribute the damaged palms and standing palms layers to the “MiniGrid” for each management zone. I created two new fields: Damage per Tree and Uncertainty. Damage per Tree (D_PERT) is a ratio of tree damage in a cell. It was calculated by dividing the number of damaged trees in a cell by the total number of trees in that cell. Uncertainty is a measure of a cell's total tree population calculated by dividing $(\frac{1}{\sqrt{x}})^2$, where x is the number of standing palms in a cell. D_PERT normalized tree density while Uncertainty gave weight to cells with more trees. I plotted D_PERT and Uncertainty using bivariate symbology. Cells with a high damage ratio and a low uncertainty value were indicators of potential breeding sites.

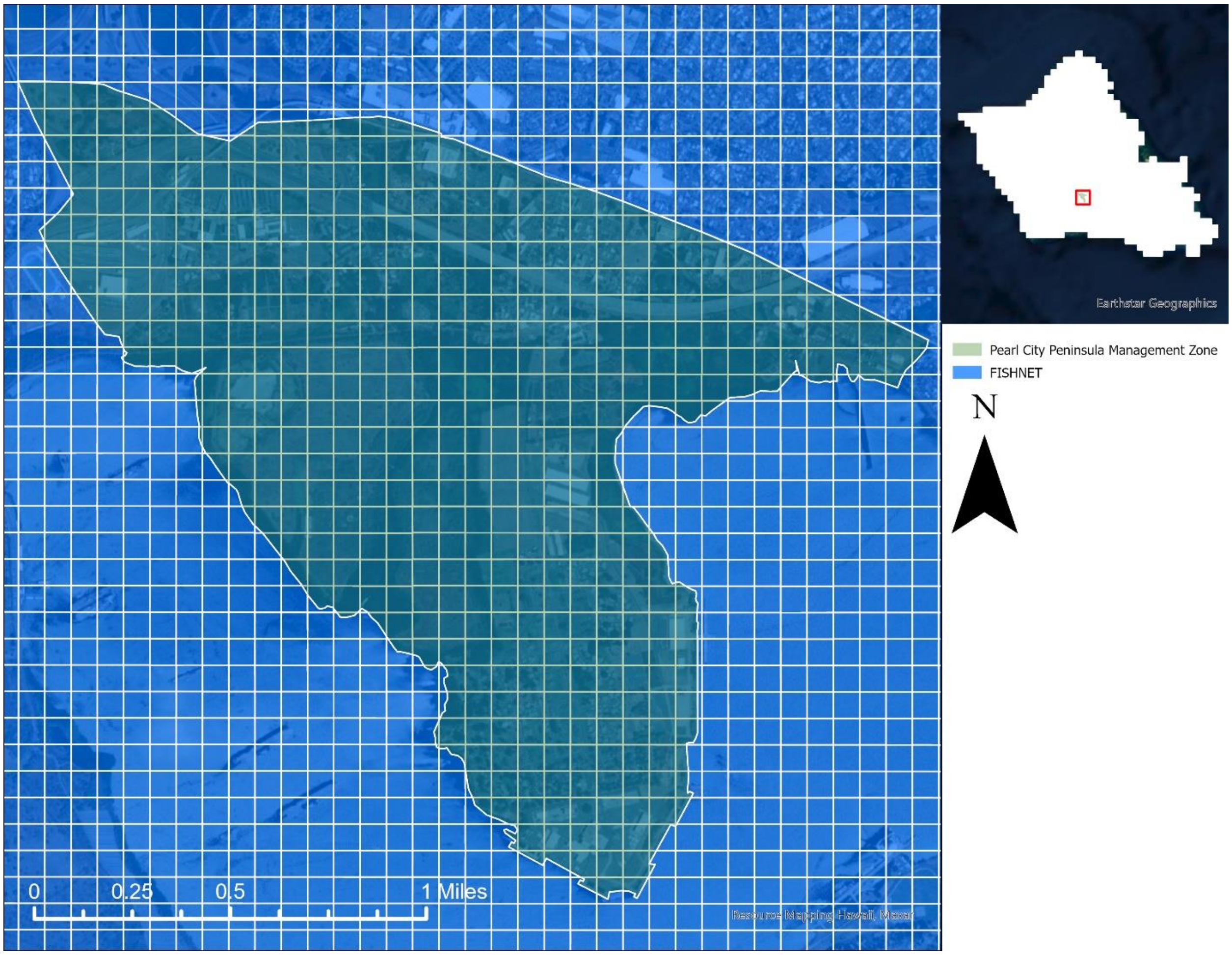

Figure 10. FISHNET for Pearl City Peninsula.

Hot Spot Analysis

Using ArcGIS Pro's 'Near' tool, I found the shortest distance between every damaged tree at Pearl City Peninsula to the closest known breeding site. 50-meter buffers (Figure 11) were created around every damaged palm in Pearl City Peninsula based on a histogram distribution of the distances. Similar to the FISHNET's process, the damage ratio and Uncertainty value for each buffer were calculated. Excel's Regression Analysis tool was used to calculate the expected/estimated distances from each damaged tree to the closest known breeding site.

I assumed that beetles caught in traps were intercepted while traveling between food sources and breeding sites. Straight lines were drawn from damaged trees through all traps that fell within a tree’s estimated distance (Figure 12). Traps that did not fall within a tree’s estimated distance were not used. However, if a trap was within the range of another tree's estimated distance, then it was used for that tree's analysis. I placed points at the ends of every line, where the number of points was weighted by the number of trap catches. Traps with more catches had more points and a higher "pull" because trap catches are an indicator of CRB presence. I used a weighted average (Table 1) to determine the number of points for each line. Traps weighting was used when a damaged tree had lines going through more than one trap. It was necessary to use trap finds as a directional pull because much remains unknown about the direction and flight patterns of CRB (K. Weiser, personal communication, February 22, 2021). The points were turned into a heat map to illustrate the likely locations of breeding sites.

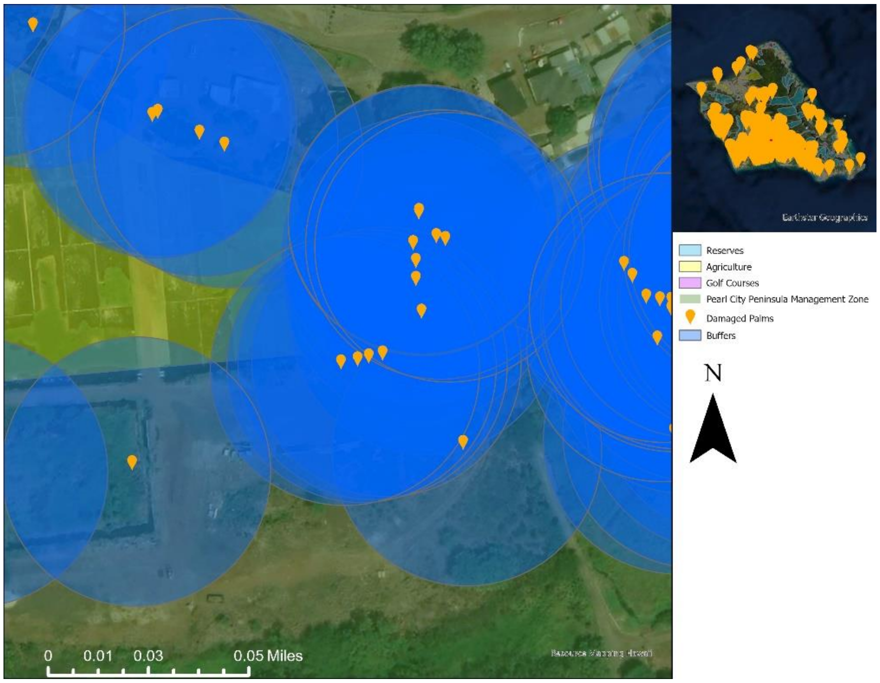

Figure 11. 50-meter buffers around damaged trees at Pearl City Peninsula.

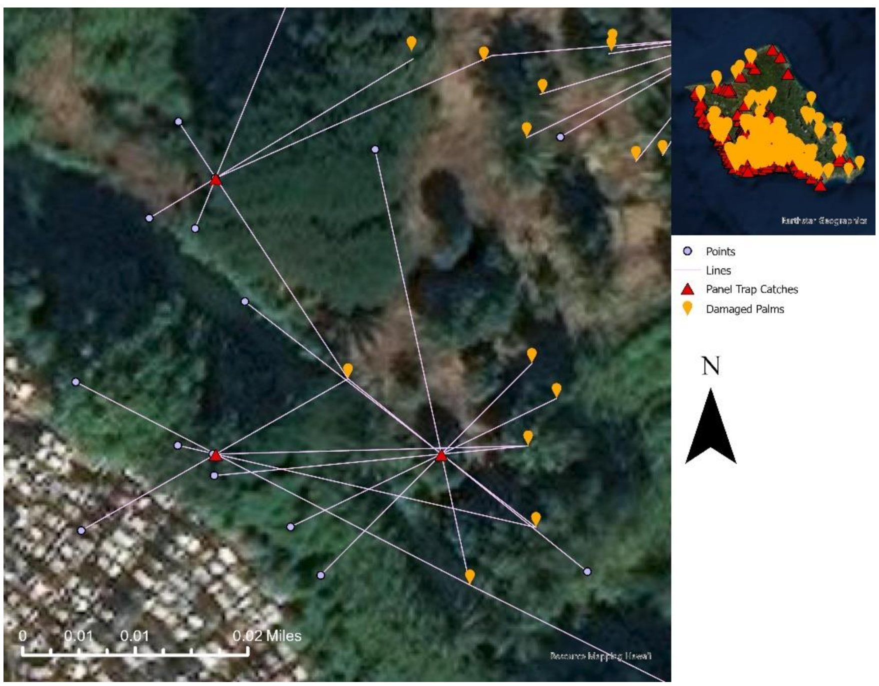

Figure 12. Trap directionality. Lines were drawn from damaged trees (orange pins) through traps (red triangles). Points were placed at the ends of each line.

Calculating the Number of Points

The estimated distance for a tree goes through three traps (Table 1). The number of points was found by multiplying each trap's percentage of the total catches by the weighted average and rounding. Trap #1 received 11 points, Trap #2 received 3 points, and Trap #3 received 27 points. Trap #3 had the most points and the highest weight because it had the most catches.

Table 1. Example showing how a weighted average of trap catches was used to calculate the number of endpoints for a tree's lines.

Table 1. Example showing how a weighted average of trap catches was used to calculate the number of endpoints for a tree's lines.

A	B	C	D
Trap #	# of Trap Catches	Percent (%) of Sum	# of Points (Rounded)
1	20	25.97	11
2	5	6.49	3
3	52	67.53	27
Sum	77		
Weighted Average	40.64		

Validation & Practical Applications

I visited the Pearl City Peninsula Management Zone (Figure 13) with members of the CRB Response to validate my methodology. The main goal was to compare the abilities of the produced maps to accurately predict the locations of potential breeding sites. A secondary goal was to test the practicality of using my maps in the field with Esri-based applications used by the CRB Response.

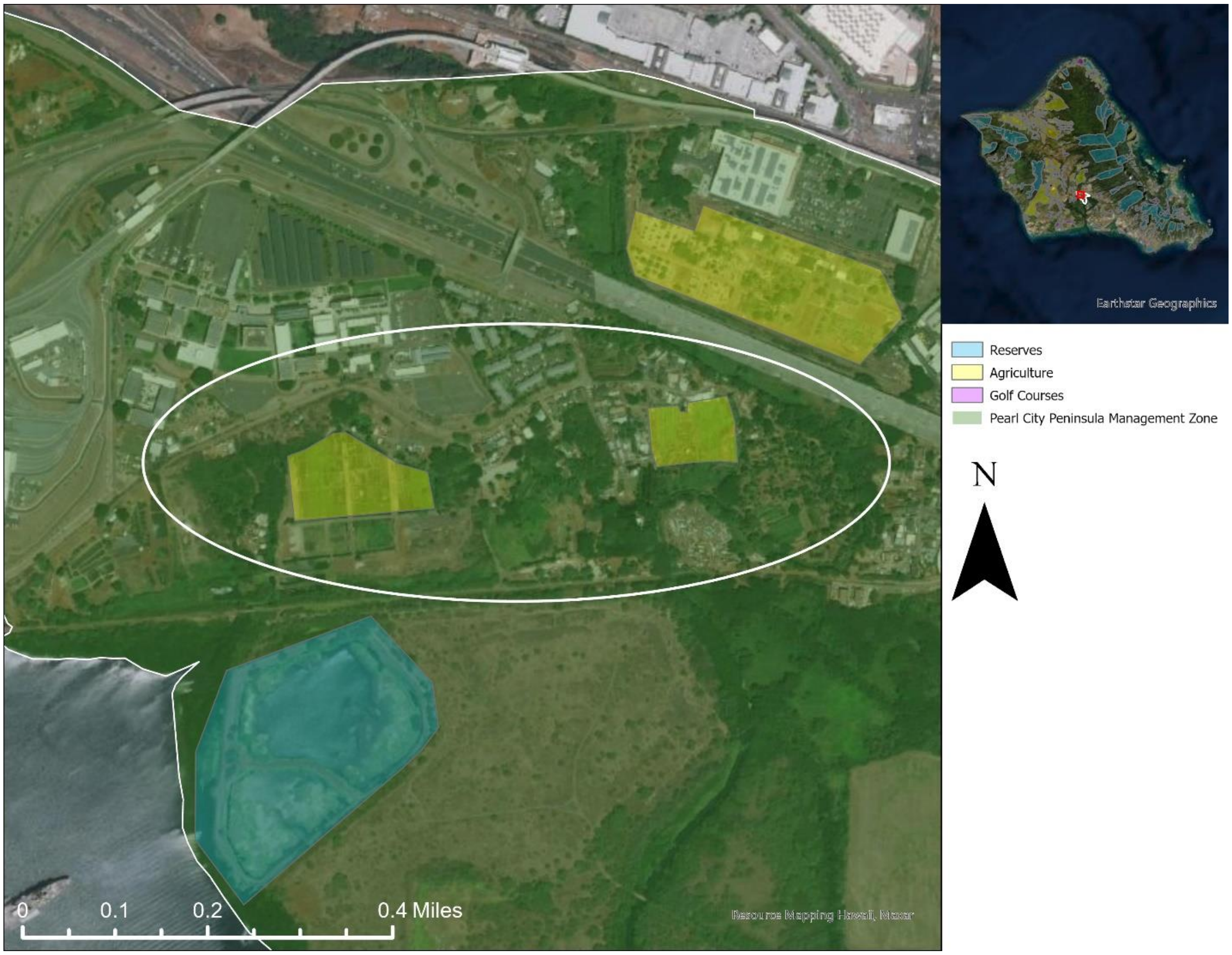

Figure 13. Map of the validation area at Pearl City Peninsula.

Results/Outputs

Potential Hosts Maps

A palm map shows the locations of all current and potential CRB hosts. I digitized a total of 5,228 palms. Pearl City Peninsula had 2,462 palms (Figure 14), Iroquois - Sugarland had 1,039 palms (Figure 15), and West Loch - Kapolei had 1,727 palms (Figure 16). This output provided the number of palms per cell when creating the FISHNETs.

Figure 14. Pearl City Peninsula's palm map.

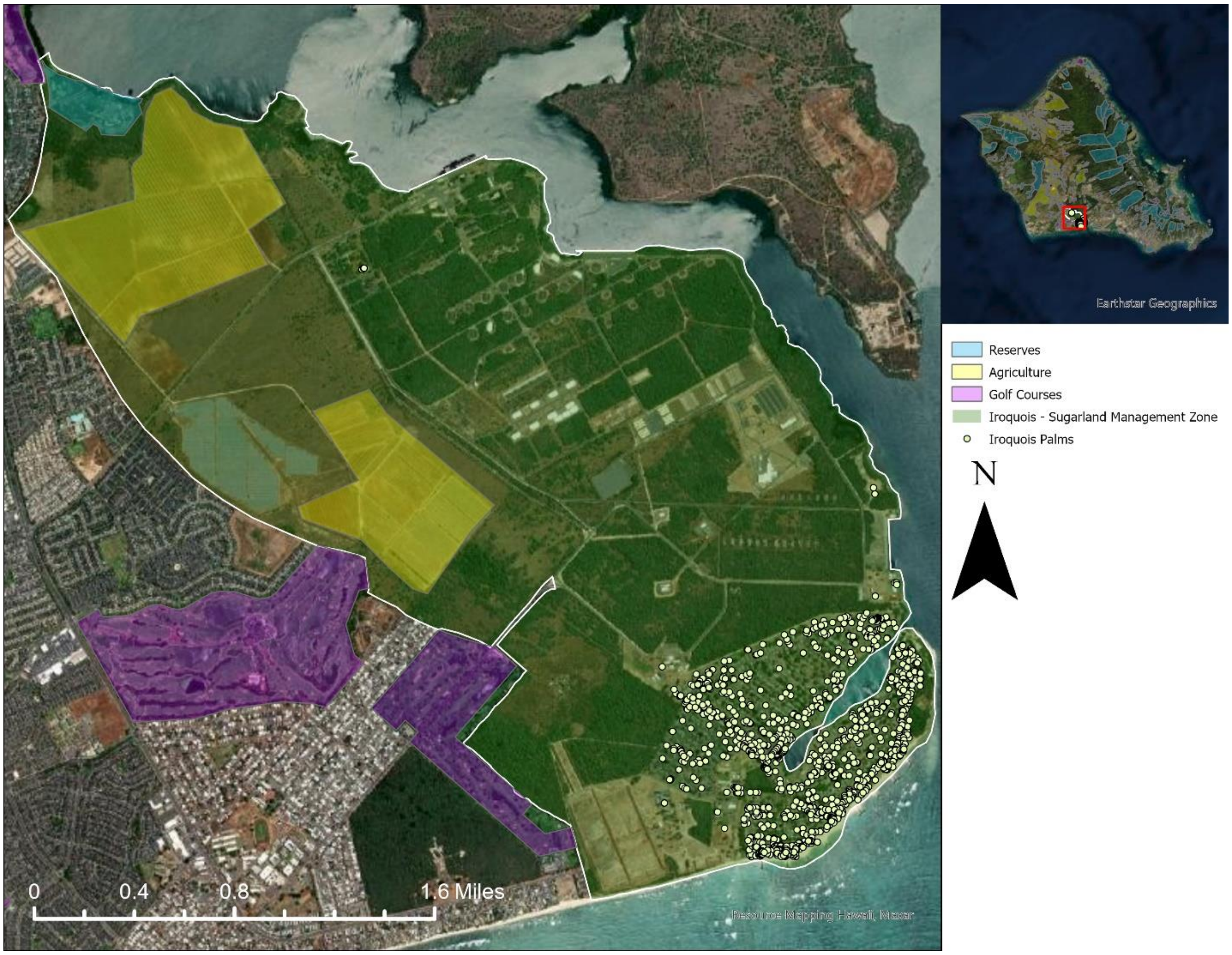

Figure 15. Iroquois - Sugarland's palm map

Figure 16. West Loch - Kapolei's palm map.

FISHNET Analysis

The FISHNETs show the likelihood of CRB breeding sites appearing in each cell. Bivariate symbology simultaneously displays D_PERT and Uncertainty. Breeding sites are more likely to be in cells with a high damage ratio and a low uncertainty value (i.e., pink cells) because it indicates a large amount of CRB activity on a large number of trees. This method emphasizes cells with a high damage rate and many standing trees. Pearl City Peninsula (Figure 17) and Iroquois - Sugarland (Figure 18) each had 14 cells that can be prioritized as areas to search for breeding sites. West Loch - Kapolei (Figure 19) had 6 priority cells.

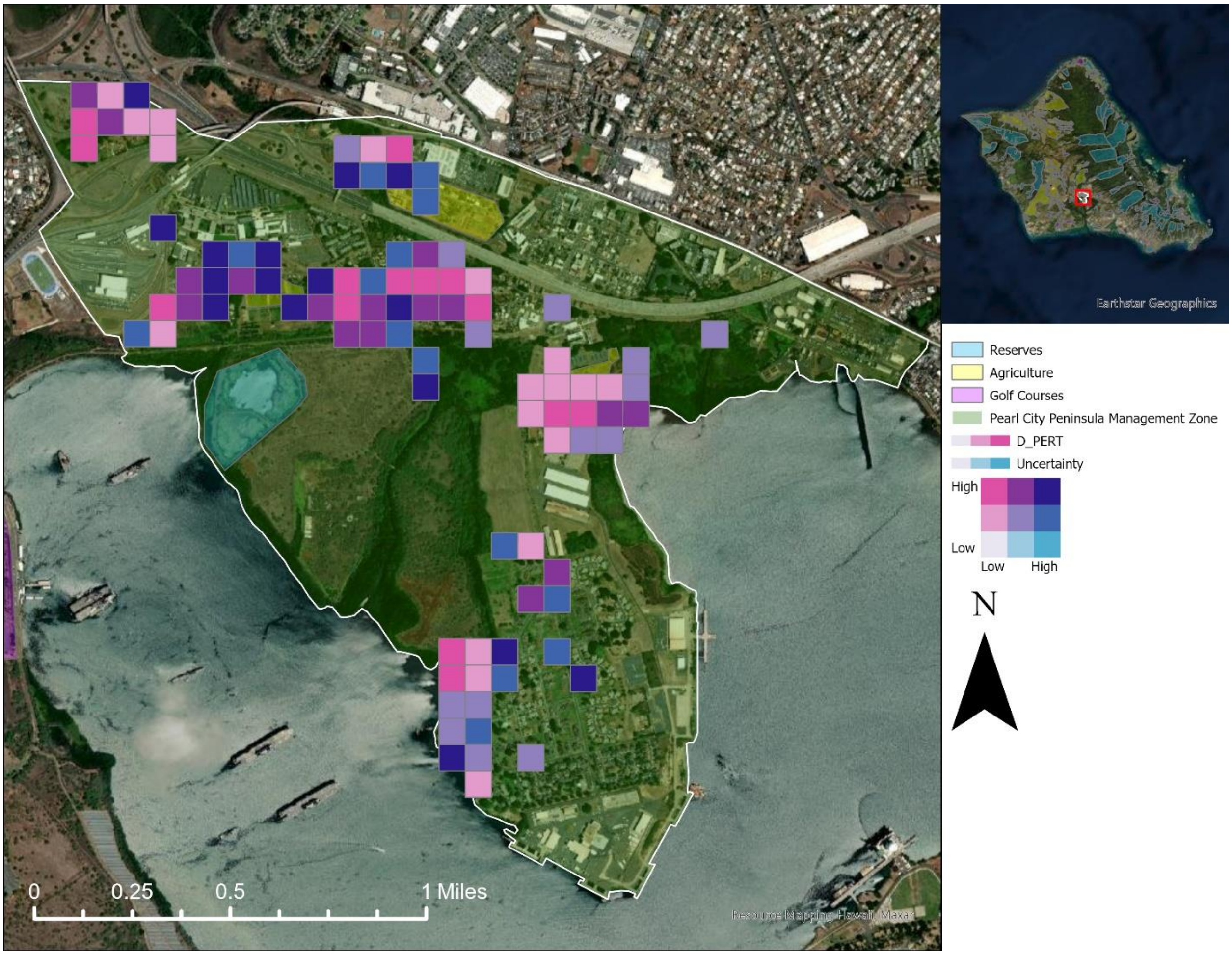

Figure 17. Pearl City Peninsula's FISHNET. Pink cells are priority areas to search.

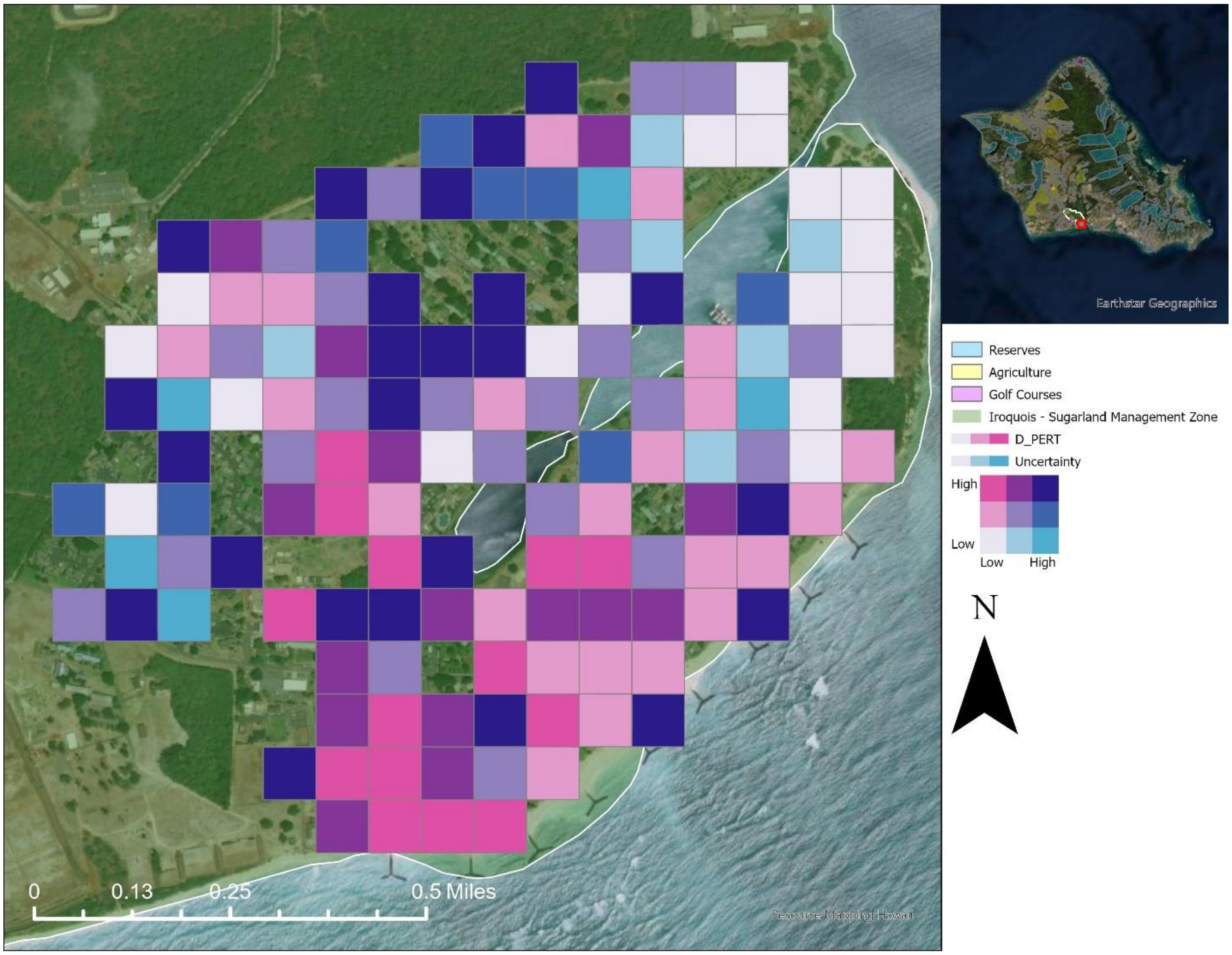

Figure 18. Iroquois - Sugarland's FISHNET. Pink cells are priority areas to search.

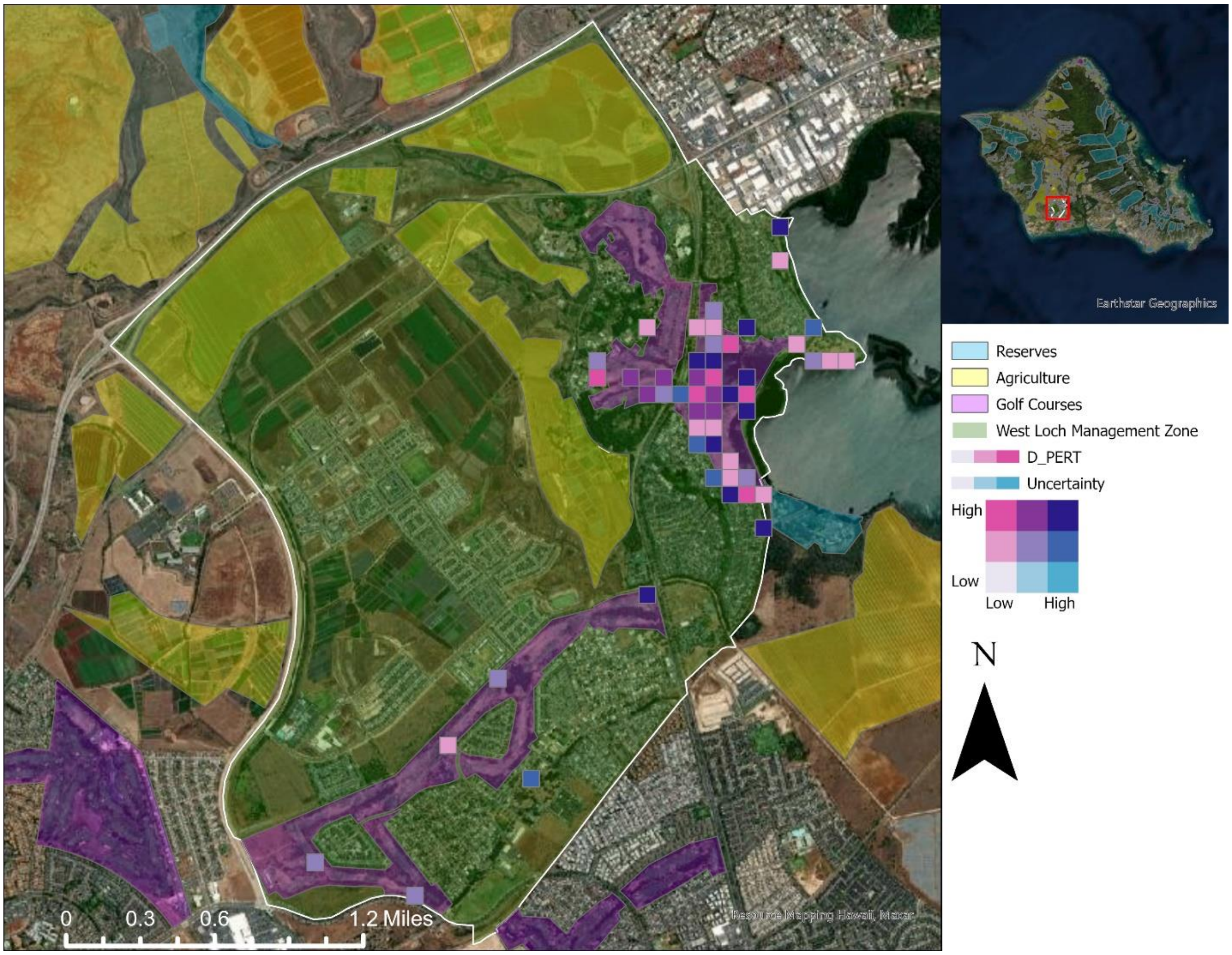

Figure 19. West Loch - Kapolei's FISHNET. Pink cells are priority areas to search.

Heat Maps

The following heat maps (Figures 20, 21, and 22) show the likelihood of finding breeding sites based on the relationship between the proximity of damaged trees to traps and the number of beetles caught in each trap. Hot spots indicate a higher likelihood of CRB breeding sites. Breeding sites can be outside the heat maps because this process assumes that captured beetles are caught while traveling between breeding sites and food sources. This process also assumes that trap catches are an indicator of breeding sites. I put the locations of known breeding sites onto each heat map to compare where known sites are versus where my maps predict them to be. There appears to be an overlap between the known breeding sites and the hot spots. Hot spots without known breeding sites are areas of concern to be searched.

Figure 20. Heat map for one section of Pearl City Peninsula. Known breeding sites are overlaid on top of the heat map for comparison of known versus predicted locations.

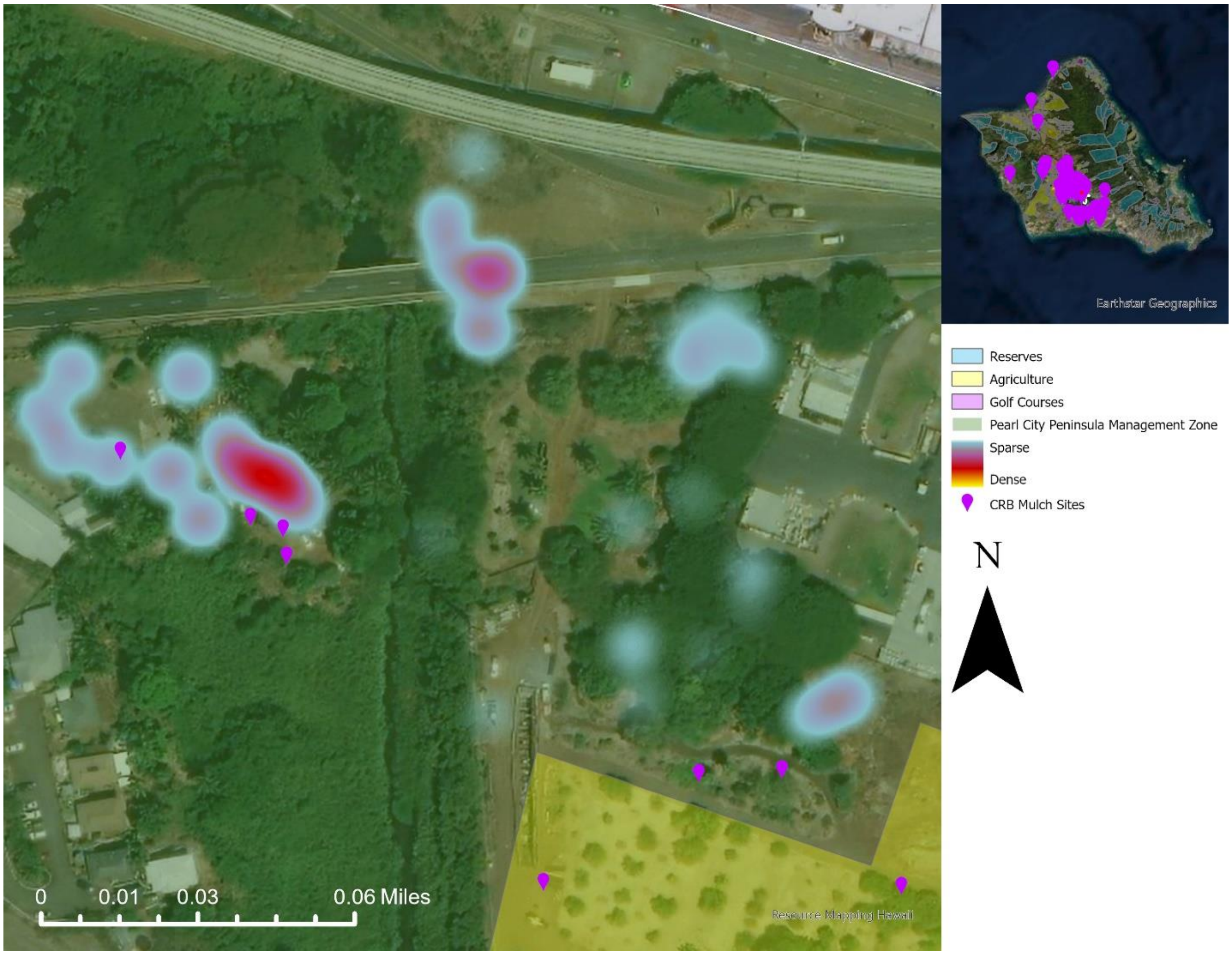

Figure 21. Heat map for a section of Pearl City Peninsula. Known breeding sites are overlaid on top of the heat map for comparison of known versus predicted locations.

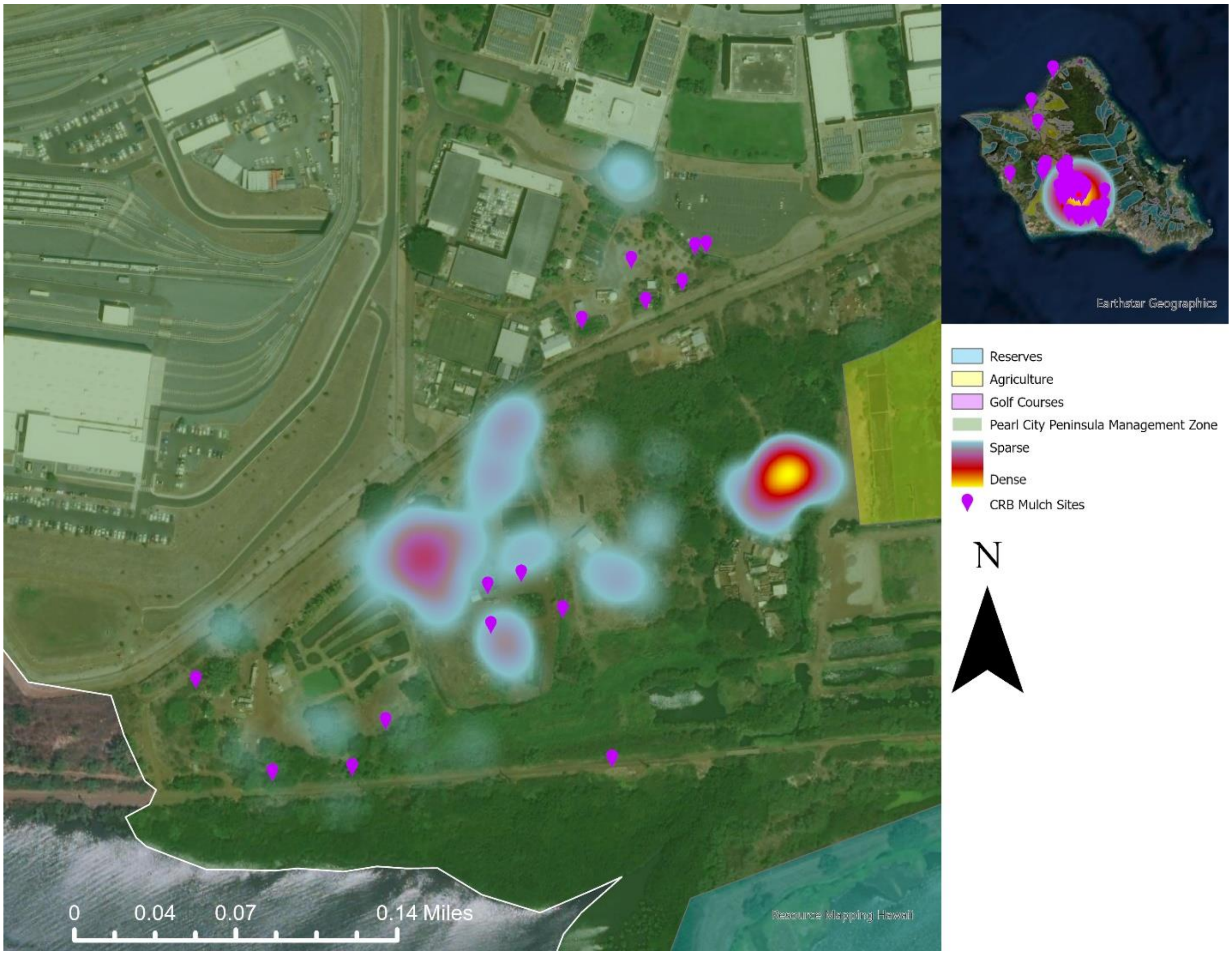

Figure 22. Heat map for another section of Pearl City Peninsula. Known breeding sites are overlaid on top of the heat map for comparison of known versus predicted locations.

Combined Heat Map & FISHNET

A combined heat map and Fishnet (Figure 23) show the potential relationship between high-priority cells and hot spots where both methods suggested similar areas to search for breeding sites.

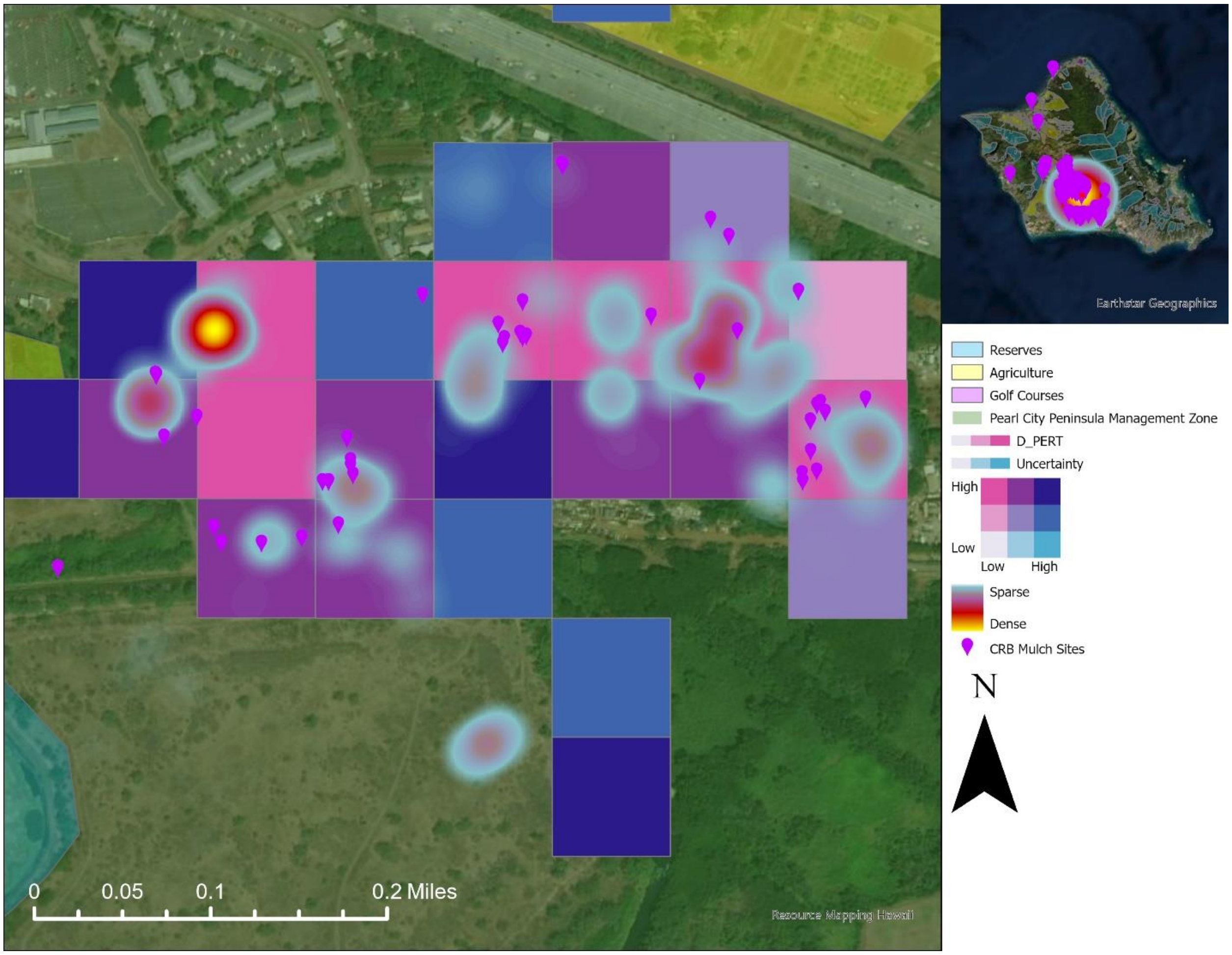

Figure 23. Combined Heat Map and FISHNET for Pearl City Peninsula.

Field Validation

I performed field validation on February 8, 2022, with members of the CRB Response. We surveyed areas of Pearl City Peninsula (Figure 24 and Figure 25) for potential breeding sites using the FISHNET and heatmap. While we were unable to find larvae, both maps did point to potential breeding sites/materials. Both maps worked well with ArcGIS Field Maps.

Figure 24. An area of Pearl City Peninsula surveyed during the field validation.

Figure 25. An area of Pearl City Peninsula surveyed during the field validation.

Discussion

Potential Outcomes

The results of this project provide the CRB Response with the locations of high-priority areas to search for breeding sites within three of their Management Zones. The methods and outputs can be combined with current eradication strategies to more efficiently find breeding sites. For example, my outputs can supplement the CRB Response's canine crew by providing the general locations of areas to search for CRB. The methodology used to create the risk maps can be replicated for other currently infested areas or areas with a history of CRB establishment. Finding breeding sites will help to protect coconut palms in both infested areas and areas without active CRB populations, such as Waikiki, which will benefit Hawaii's tourism industry. Local communities that value and utilize coconuts will benefit from its protection. Culturally and economically valued plants such as hala and kalo will be protected. Local organizations that manage culturally and economically valued plants capable of becoming CRB hosts, such as hala and kalo, will benefit from improved CRB management. The maps can be shared with other natural resource managers who are responsible for areas or species that are threatened by CRB. Landowners can use the risk maps to see where in their properties are at risk of CRB intensification. This will help conservationists in protecting native Hawaiian plants by aiding in the eradication of a major pest. Any potential reduction in CRB will benefit areas that do not yet have established CRB populations. This includes the neighboring Hawaiian Islands and the Americas.

Comparison of FISHNET versus Heat Maps

The Pearl City Peninsula FISHNET and Heat Maps appear to point to similar areas, so perhaps one method can supplement the other. The FISHNET requires fewer data and fewer steps than the Heat Map. Therefore, the FISHNET should be used for landscape-scale analysis to find general areas of concern. The Heat Map can supplement the FISHNET by pinpointing areas within priority cells that could be searched for breeding sites. The Heat Maps are also more practical for field use because they point to actual areas (i.e., hot spots) rather than a general square-shaped area of concern.

Limitations

Assumptions had to be made when designing the methods as much remains unknown about CRB behavior. Knowledge gaps exist regarding what CRB do when not feeding or residing at breeding sites. This was the justification for the assumption that beetles are caught while traveling between breeding sites and food sources. Dynamic sampling locations created challenges with using date-time series data. The variables used in this project were chosen to account for the constantly changing conditions of the study sites. A time lag exists between when CRB feeds on a palm and when the damage is visible to humans because of the growth pattern of palm fronds. CRB is often already established by the time damage is visible to humans.

Therefore, more focus should have been placed on trap catches instead of damaged tree surveys because traps are checked weekly while tree surveys are done yearly.

When digitizing palms, I sometimes had to make a judgment call on whether a tree was a host or non-host of CRB. I assumed a tree was a host if I was unsure. Google Street View is unavailable in military-owned areas, so it is likely that I overcounted the number of palms. However, there should be minimal effect on the FISHNET analysis because it mainly occurred in cells without damaged trees. The same should apply for the heat maps because most of the relevant trees were already injected and digitized by the CRB Response.

Application to Virgin Areas

One challenge is locating breeding sites in newly infested areas. The CRB Response is now recording trap catches on the North Shore of Oahu. My methods require the presence of trap catches and damaged trees. Therefore, the methods I developed for heavily infested areas might not be applicable to North Shore and other newly invaded areas until more signs of CRB intensification are recorded.

Validation

The field validation was likely unable to locate actual CRB larvae because of a combination of previous tree injections, best management practices by local farmers, and recent flooding. Tree injections are responsible for a decreasing trend in the number of captured beetles in several management zones, including Pearl City Peninsula. Landowners are now more aware of CRB, so they've taken individual actions to manage their properties (Figure 26). In December 2021, heavy flooding likely killed existing larvae populations. Our site visit was too early, where not enough time would have passed for new beetles to reestablish. However, it was positive that the risk maps pointed to potential breeding sites/materials (Figures 27 and 28) despite the lack of larvae.

Figure 26. Fishnet used to catch CRB at a farm.

Figure 27. Suspected breeding site on a farm in Pearl City Peninsula.

Figure 28. Former breeding site suspected to have contributed to many trap catches in the near vicinity.

Conclusions

The Coconut Rhinoceros Beetle is a major threat to Hawaii's ecosystems, economy, cultural resources, and agriculture. This capstone project created two methods to predict the locations and likelihood of CRB breeding sites and intensification, respectively. One method used the relationship between the proportion of damaged trees and the number of standing trees. The other method used the relationship between the proximity of traps and the number of trap catches. Potential breeding sites were found during field validation despite the lack of larvae. Combining this project's methods with current eradication strategies will increase the likelihood of eradicating CRB on Oahu.

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