Restoring Ecosystem Services and Biodiversity through Cost-Effective and Resilient Agroforestry Systems

MAY 12, 2022

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**Report for the Natural Resources Conservation Service, Pacific Island State Area Office.
Conservation Innovation Grant #NR1892510002G003**

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Opening ceremony at our first Puʻulani community planting work day at Kākoʻo ʻŌiwi in January 2019; over 200 volunteers came that day (https://www.uhero.hawaii.edu/news/view/346).

Since September 2018, our project team, composed of University of Hawaiʻi faculty and students, Kākoʻo ʻŌiwi staff, and other partners have worked together to: 1) design, implement, and monitor 10 agroforestry demonstration plots and buffer areas in Heʻeia, Oʻahu (*objective* 1); 2) publish peer-review and practitioner-oriented material on agroforestry, functional traits, and ecosystem services (*objective* 2); and 3) carry out two agroforestry workshops (*objective* 3).

This effort has included substantial labor effort, including over 200 person hours of design and planning, 300 hours of clearing, 800 hours of planting, and well over 2000 hours of management (mainly weeding). Our project team has additionally spent over 1500 hours on monitoring and data analysis. A portion of the time spent on the clearing, planting, and management was covered by our Conservation Innovation Grant. However, the majority of management labor and nearly all of the monitoring and data analysis labor was covered by complementary funding sources including from the University of Hawaiʻi College of Social Sciences, the University of Hawaiʻi Department of Natural Resources and Environmental Management, the National Science Foundation (Zoe Hastings PhD fellowship), the Heʻeia NERR, and the University of Hawaiʻi Sea Grant College Program. We also successfully held many community work days prior to COVID-19 and continue to provide opportunities for community members to engage in the space and contribute to its management. Given the high financial and labor cost of clearing, planting, and on-going management restoration, such leveraging power has been critical to the success of our grant.

This report primarily covers our achievements of objectives, deliverables, and milestones from October 2018 to October 2020. We received a year-long extension to complete components of objective 2 and objective 3, which were delayed with the COVID-19 pandemic. We thus report on achievement of objectives 2 and 3 through May 2022. We have successfully met all objectives of the grant and have also secured funding for continued management and monitoring of our collaborative biocultural restoration project. We are grateful to the Natural Resources Conservation Service for the support that our Conservation Innovation Grant provided and hope to continue the collaboration with NRCS into the future. In addition to our successes, this project has also generated strong lessons learned which can be applied to future restoration efforts.

OBJECTIVES:

Objective 1: *Establish, manage, and monitor ten agroforestry demonstration plots in collaboration with* Kākoʻo ʻŌiwi *in Heʻeia, Oʻahu.*

DESIGN AND ESTABLISHMENT:

From October 2018 through March 2019, our project team successfully designed and established ten agroforestry demonstration plots as well as one control plot where the original non-native vegetation remains. Baseline soil (soil carbon, soil health, and microbial analyses) and vegetation (plant richness, diversity, cover; above-ground carbon) measurements were taken in each plot prior to clearing in October 2018 (see monitoring section).

The process of site selection, defining project objectives, and plot design was a collaborative effort, with an emphasis placed on ensuring that the demonstration plots met CIG objectives as well as fit into the long-term vision and goals of Kākoʻo ʻŌiwi in order to ensure the sustainability of the project. Kākoʻo ʻŌiwi's mission is to perpetuate the cultural and spiritual practices of Native Hawaiians and the demonstration site reflects this mission (see Hastings et al. 2020, Conservation Science and Practice).

After many initial meetings, we held two site visits with Kākoʻo ʻŌiwi staff as well as additional partners, including the Heʻeia NERR and Oahu RC&D (who had previously established a small agroforestry project) to formally explore potential restoration sites in the fall of 2018. Prior to final selection of sites, we held a project planning meeting to define project objectives, vision, and roles. From this meeting we determined the project vision and goals (*Figure 1*). We then held a final selection visit where we decided to focus restoration in Puʻulani, an elevated area just above the wetland (*Figure 2*). We selected this site for several reasons. First, this area is within Kākoʻo's current management focal area, which ensures that long-term staff resources could be focused there. Second, this area is optimal for access and use as a demonstration site as it is accessible by foot and vehicle. Third, a Kākoʻo ʻŌiwi staff member, Mahealani Botelho, had recently been put in charge of restoring the area for cultural, biological, and economic values, representing an ideal opportunity for a productive UH-Kākoʻo ʻŌiwi collaboration.

Figure 1: Visioning meeting with UH research team in September 2018, Kākoʻo ʻŌiwi, and Heʻeia National Estuarine Research Reserve (NERR) staff. Broad objectives for agroforestry on Kākoʻo lands were: 1) support community connections to the forest and each other; 2) create multifunctional systems that contribute to the overall landscape mosaic; 3) produce local non-timber forest products and food; 4) increase ecosystem services (water holding capacity; erosion control; carbon; biodiversity); 5) contribute to Kākoʻo's financial sustainability; 6) conserve native species and make them more accessible to the community; 7) create low-management systems; and 8) contribute to climate resilience (Photos: Leah Bremer).

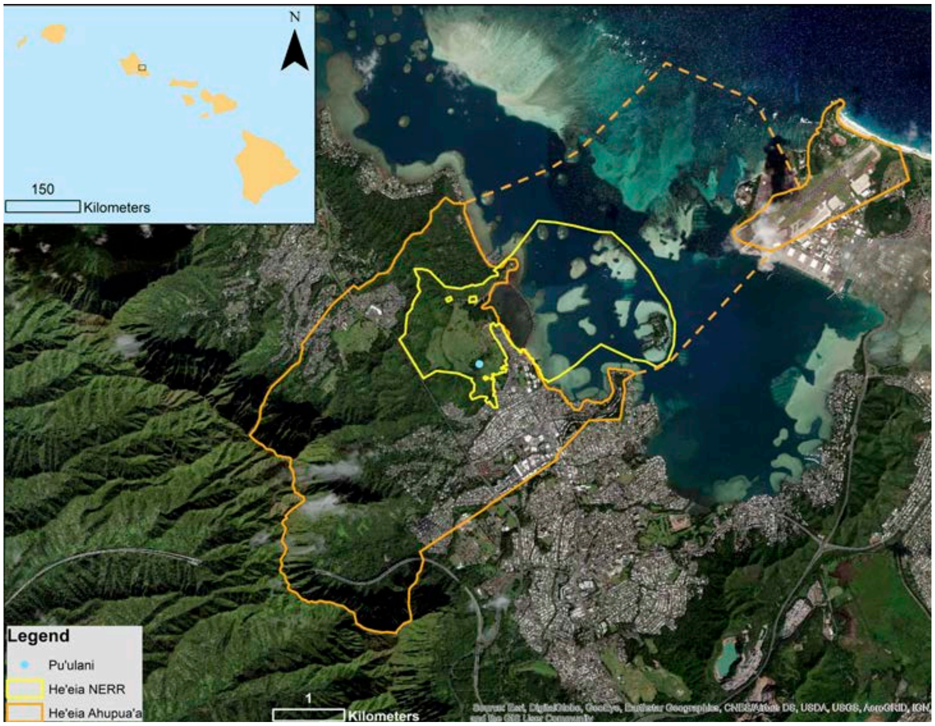

Figure 2: Pu'ulani agroforestry restoration site, in the He'eia ahupua'a, Ko'olaupoko, O'ahu. Noted: solid orange line represents ahupua'a boundaries in the Hawai'i Statewide GIS Program Ahupua'a GIS Layer. However, historical boundaries would have included the He'eia fishery within the ahupua'a boundaries and is approximately represented with the dashed orange lines following the ahupua'a of He'eia land commission award (Ahupua'a of He'eia and its appurtenant Fishery, L.C.Aw.10613, Ap.1 to A. Paki. From: Public archives of Hawai'i, Letter Folder 244-B, H.A. & R.L. 3/3/47). Source: Melone et al. 2021, Agriculture.

Figure 3: Map of agroforestry restoration and control plots at Kako'o 'Oiwi in He'eia, Oahu (credit: Zoe Hastings).

After agreeing upon the restoration site and project objectives, we established the actual restoration plots in December 2018, carefully measuring out the 10 plots along the ridge (*Figures* 3 & 4). We ended up needing to reduce the plot size to 12 m x 15 m in order to fit the plots and 5 m in between for a more flexible planting area, as well as to include a control plot for long term visual comparison. Including buffer areas above the plots and between plots, over 3000 m^2 were planted (1500 m^2 of each treatment). An additional 6 randomly placed, 2 m x 2 m subplots were additionally established for long-term monitoring of vegetation, soils, and other ecosystem services, which provide quantitative data to complement the visual demonstration.

Figure 4: A key first step was to select the location of the restoration plots so that they would be accessible for management and use. We selected a ridge above the wetland, Puʻulani. Photographed above are the Kākoʻo farm staff helping to measure out the 10 intervention plots and control plot (Photos: Zoe Hastings).

The demonstration site at Puʻulani and the species that were selected provide multiple ecosystem services including cultural and biodiversity benefits, alongside traditional and local food production (including banana, mamaki, awa, plumeria as well as mango, guava, breadfruit, mountain apple, and other species already planted in the area). To inform the design, Botany PhD student, Zoe Hastings, conducted a thorough literature and database search for functional trait data of over 100 candidate species, including all those on the NRCS Mixed Agroforest technical note. The NRCS Mixed Agroforest technical note guidelines were carefully followed (see supplementary material table 1). Zoe then led a participatory species selection and design process with Mahealani Botelho and the Kākoʻo ʻŌiwi team (*Figure* 5). Kākoʻo ʻŌiwi selected a subset of the species listed by NRCS but our approach ensures that the non-listed, selected species have ecological, management, and cultural values that are functionally equivalent to many of the listed species. The participatory functional trait species selection process encouraged ownership of the project by Kākoʻo ʻŌiwi and ensured that the species selection represented food-producing non-timber forest products (NTFPs) of high interest to the land manager (see supplementary material table 2 for species list as well as species cards designed by Maile Wong and Zoe Hastings). Moreover, having flexibility in species selection was critical to establishing shared goals with the landowner, without which the demonstration would not have been possible nor sustainable. The participatory and functional trait design process has been published in Conservation Science and Practice and is explained in the Puʻulani Project Brief (see objective 2). The list of candidate species and trait data is available here.

Figure 5: The research team and Kākoʻo staff worked to select a species mix that combined ecological goals (erosion control and early successional facilitation) as well as cultural values. Photo: Leah Bremer

The next stage was clearing, which was carried out in December 2018. Large java plum and other non-native canopy species were removed by a professional arborist (paid for by the He'eia NERR and Kākoʻo ʻŌiwi). Understory vegetation was cleared by UH and Kākoʻo ʻŌiwi research staff as well as the focus of a community work day (*Figure 6*).


Figure 6: The next phase was clearing, which we did through community work days, joint researcher and staff work days, and funding from the He'eia NERR to professionally trim and remove some invasive vegetation. Photos show initial clearing done by UH and Kākoʻo staff (top left); final clearing post arborist during a community work day (top right); Kākoʻo crew supporting professional arborist in removing large non-native java plum trees (funding for arborist was provided by Kākoʻo ʻŌiwi and the Heʻeia NERR (bottom left); UH and Kākoʻo staff continue hand clearing. Photos: Leah Bremer


Figure 7: Native and other culturally and economically useful plants were purchased primarily from the native plant nursery Hui Ku Maoli Ola just mauka of Kākoʻo ʻŌiwi. Photos: Zoe Hastings and Leah Bremer

The next stage was planting, which started January 9th, 2019 at the initial work day and continued through April. Over 2000 plants representing 30 native and polynesian species and four introduced species were planted by the UH and Kākoʻo ʻŌiwi teams as well as by over 300 volunteers at various community work days and educational visits (*Figures* 7 & 8). All of the species produce NTFPs with important cultural and economic value, including five species specified in the NRCS Mixed Agroforestry Technical Note (see supplementary material table 1). Following the NRCS Technical Note, our demonstration area contains high species, functional, and structural diversity that explicitly improves ecosystem services, including reducing non-native species, erosion control, water quality improvement, and carbon sequestration, while also providing a wide range of NTFPs. In accordance with the NRCS Mixed Agroforestry Technical Note, this area of the farm has a resource conservation focus, so NTFPs will provide secondary benefits through time. We tracked volunteer responses and it was clear that the cultural and educational benefits of the agroforest were already being experienced immediately after planting.

In March 2020, we added an additional unfenced plot as requested by NRCS. Having a fence around the entire restoration area for the first two years was Kākoʻo ʻŌiwi's strong preference, and there was more interest in testing two functional trait treatments (erosion control and succession) as more useful for farm management than the fencing treatment. However, the additional unfenced plot provides a visual demonstration of unfenced vs. fenced for the first year of establishment. After the first two years of establishment, Kākoʻo ʻŌiwi preferred to remove the fence and control pigs through hunting as the management of the fence reduced available labor time for other management (e.g. planting and weeding). Vulnerable species such as wiliwili were fenced individually.

Figure 8: Since January 12, 2019 the UH team, Kākoʻo staff, and 100s of volunteers have turned a sea of flags into a budding agroforest. While many of the ecological objectives will take a long time to realize, we have already observed some social and cultural benefits, including numerous students from pre-school to college learning about agroforests. Photos: Leah Bremer, and Zoe Hastings

Figure 9: Maile Wong helps to lead a Kaiser Permanente work day where families help to plant the additional unfenced plot. Shown here planting koa (Acacia Koa).

MANAGEMENT

Since the initial planting, the project team and thousands of volunteers have contributed to the management of the site through weeding and supplemental planting (*Figure* 10). We carried out over 20 public community day work days varying from 200 to 5 people (depending on COVID restrictions) during the project time period. Work days were both to accomplish management objectives (weeding and planting), but also to educate the general public as well as specific groups (including Kaiser Permanente, the Hawaiʻi Society for Conservation Biology, Waipā Foundation and many University of Hawaiʻi courses).

We also established a drip irrigation system early on, but it was not durable enough to last beyond a year. We held at least monthly work days up until the COVID-19 pandemic and also supported several undergraduate students, most notably Maile Wong who has worked on the project half time (20 hours per week) since March 2019. She was supported partially by our CIG grant, but now is supported by Sea Grant.

We also continue to propagate and plant additional plants as supplements to the plots. Given the low survival of some of the canopy species (e.g. ʻōhiʻa lehua), we planted kukui seeds throughout the plot, many of which have come up as seedlings. We have also out-planted approximately 100 hala, ʻōhiʻa ʻai, noni, and other propagated seedlings. This should help to establish a faster growing canopy. We also outplanted 10, 1-gallon avocado trees, several ulu trees and citrus trees purchased from Maui Native Nursery and Waiahole Nursery. In sum, we are learning from what survives well under the climatic and management conditions of Puʻulani and are adapting our management and planting to achieve these goals. A summary of future management following a culturally-grounded observation approach combined with ecological monitoring can be found here.

Figure 10: Weeding and supplemental planting; Volunteers helping to outplant a'ali'i.

In July 2020, we harvested our first Iholena lele, which was exciting for the team and project. Additional plants (e.g. pohinahina, laʻi and others) have been harvested for hula, tea, and lei (*Figure* 11).

Figure 11: Harvesting our first Iholena at the Puʻulani agroforest restoration site.

MONITORING AND RESEARCH

Once the plots were set up, the project team conducted an extensive baseline of vegetation (species diversity and cover), above-ground carbon, soil carbon, microbial processes, and soil health (*Figure 12*).

Baseline soil (soil carbon, soil health, and microbial analyses) and vegetation (plant richness, diversity, cover; above-ground carbon) measurements were taken in each plot prior to clearing in October-December 2018.

Figure 12: The team conducted an extensive vegetation and soil baseline. We decided on metrics that would be feasible to measure over the long-term including erosion, above ground carbon, soil carbon, soil health, and plant diversity and which would complement the visual demonstration in communicating the benefits of agroforestry. Photos: Zoe Hastings and Leah Bremer.

After planting, we tagged and numbered all trees and shrubs and measured their basal diameter and height at planting to facilitate tracking of their growth and survival over time. Plant monitoring was carried out every 6 months during the official project period October 2018-October 2020 and will be carried out every year going forward. Soil health and soil carbon monitoring was carried out twice during the official project period and will be conducted every other year going forward pending funding availability (*Figure 13*). The Puʻulani plant and soil monitoring protocol can be found here.

Figure 13: Maile Wong, helps to monitor plant growth. In this picture, she is monitoring a newly planted iholena (Hawaiian banana) on May 21, 2019 (left). By August 2019, iholena plants are approximately four feet tall (right), and by July 2020 ready for harvest (lower).

MONITORING RESULTS:

EFFECTS OF DIFFERENT SPECIES MIXES ON PLANT SUCCESS AND SOIL HEALTH

We monitored the plant communities at Pu'ulani before restoration (baseline), at planting, and at 6 months, 1 year, and 1.5 years post-planting and took soil samples at baseline and 1.5 years post-planting. We analyzed the effects of the two restoration scenarios, or agroforestry species mixes, on mid- and overstory plant survival, understory plant cover, and soil health. Overall, we found that none of the indicators of restoration success we measured - plant survival, understory cover, and soil health - varied significantly between the restoration scenarios or treatments in the first two years of restoration. We prepared a draft manuscript summarizing our findings and anticipate submitting it to the peer reviewed journal *Agriculture, Ecosystems & Environment* in the summer of 2022.

PLANT SUCCESS:

Mid- and overstory plant survival did not differ between restoration treatments (agroforestry species mixes) (Table 1). We calculated survival rates for two time periods (6 mo - 1 year and 1 year - 1.5 years) because the site experienced drought conditions in the second time period. Table 2 shows the mean survival rates for each restoration scenario or treatment during the two time periods as well as the understory weed cover and canopy cover.

Table 1. *Survival rate by species over two time periods (6 months to 1 year, and 1 year to 1.5 years post-planting) for all mid- and over-story outplants in each restoration treatment (i.e., agroforestry species mix), including species in common between the two treatments at a restoration site in Hawai'i. Note that the site experienced a drought during the second time period.*

Common name	Latin name	Survival rate (%)	
		6 mo – 1 yr	1 yr – 1.5 yrs (Drought)
Erosion control treatment			
'Ohia lehua mamo	*Metrosideros polymorpha*	26.7	25.0
Mai'a iholena lele	*Musa* spp.	95.9	93.6
A'ali'i	*Dodonaea viscosa*	33.3	80.0
Pohinahina	*Vitex rotundifolia*	84.6	97.2
Early successional facilitation treatment			
Koa	*Acacia koa*	95.0	100
Aweoweo	*Chenopodium oahuense*	81.5	86.4
Pualoalo	*Hibiscus arnottianus*	88.0	95.9
Māmaki	*Pipturus albidus*	2.38	0.00
Both treatments			
'Ohi'a lehua ahihi	*Metrosideros tremuloides*	8.82	0.00
Maile	*Alyxia stellata*	12.1	37.5
'Awa	*Piper methisticum*	41.7	0.00

Table 2. *Summary of plant community characteristics at 1-year post planting, and 1.5 years post planting of two different agroforestry species mixes selected for their cultural value and functional traits (E = erosion control, S = early successional facilitation) at a restoration site in Hawai'i. The first year post-planting, the site experienced normal rainfall levels, and the next six months the site experienced drought conditions.*

	1 yr post-planting (March 2020)		1.5 yrs post-planting (October 2020)	
	E	S	E	S
Canopy cover (% cover by subplot)	71.0 ± 6.6	63.6 ± 10.3	72.1 ± 6.2	69.4 ± 10.5
Understory cover of weed species (% cover by subplot)	57.0 ± 30.7	41.3 ± 31.7	69.3 ± 21.1	64.6 ± 26.8
Survival of mid- and over-story outplants (% survival by plot)	62.5 ± 4.4	55.3 ± 10.2	84.0 ± 5.5	80.0 ± 5.1

SOIL HEALTH:

Soil health indicators are biological, chemical, and physical soil properties that affect the soil's ability to provide a suite of ecosystem services (Hubanks et al. 2019). We analyzed soil samples from Pu'ulani for 11 soil health indicators that have been selected through rigorous ecological testing and proposed as key indicators for soil health in Hawai'i (Table 3; Hubanks et al. 2019). We found that the baseline soil health at Pu'uanli was considered good and comparable to other forest sites in Hawai'i (Crow et al. submitted). One and a half years after planting, the soil health was still considered good and there was no difference in soil health between the two treatments (Figure 14).

Table 3. *Eleven soil health indicators recommended for use in Hawai'i (Hubanks 2019) and used in this study. Reproduced from Hubanks (2019).*

Indicator	Function and Interpretation
Total organic carbon (%)	As the backbone of soil organic matter, a proxy measurement of the amount of soil organic matter; higher value typically relates to benefits of multiple biological, chemical, and physical aspects of soil function
Biological Properties	
24 hr CO2 burst (μg g-1)	Soil respiration in response to readily available substrate; higher value indicates high microbial activity and high quality organic matter pools
β-glucosidase (mg p-nitrophenol kg-1 soil h-1)	Proximate microbial metabolism of amino-containing substrate; higher value indicates nutrient, predominantly N, mineralization
β-glucosaminidase	Potential N supply; higher value indicates bioavailable N forms to support soil productivity
Mineralizable nitrogen (μg g-1)	Potential N supply; higher value indicates bioavailable N forms to support soil productivity
Chemical Properties	
pH	Biological and nutrient availability; 6.0—7.0 is ideal, this is the pH range where plant essential elements are most available, and toxicities are negligible

DOC:DON ratio	Integrated indicator of the balance of organic carbon and organic nitrogen pools; lower is better; higher value indicates disturbance - high DOC indicates available microbial substrate but also potential runoff, priming, and loss if too high, DON is readily broken down by soil microbes into inorganic forms, but low values are associated with N-deposition or poor nutrient management in disturbed systems
Hot water extractable carbon (µg g-1)	Readily available metabolic substrate; higher value indicates soluble organic matter and lysed microbial cells that support microbial activity
Physical Properties	
Water holding capacity (%)	Plant-water relations; higher values indicate improved water storage
Water stable mega-aggregates (%)	Water infiltration, porosity, aeration; higher values improve retention/transport water, promote root growth, provide habitat for microbes, reduce bulk density, and resist erosion
Bulk density (g cm-3)	Infiltration, porosity, and rooting environment; lower values indicate soils that are light, aerated, porous, promote root growth, and more workable

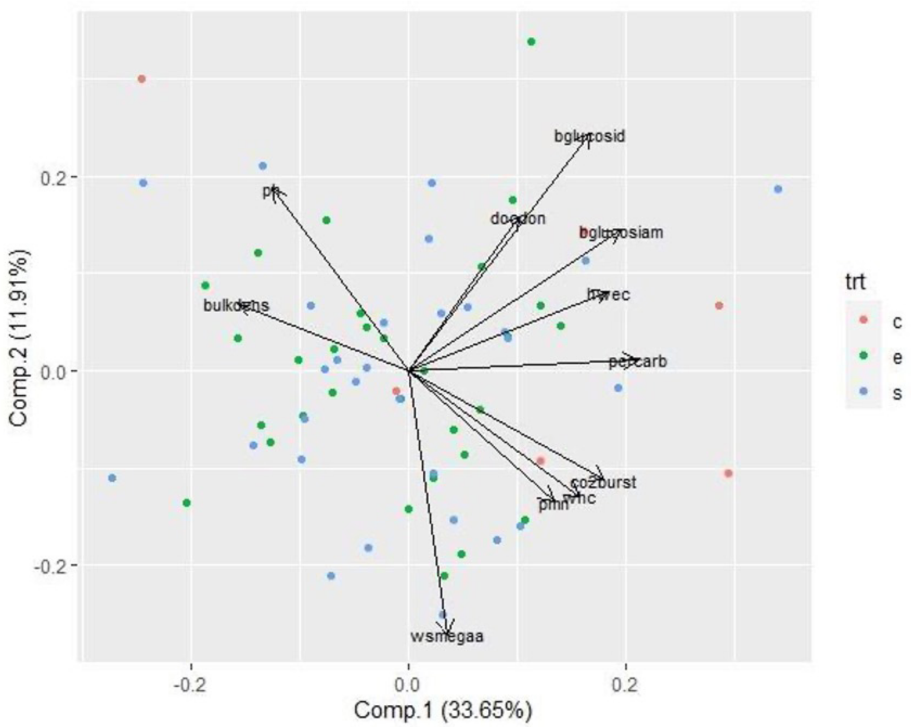

Figure 14: Principal component analysis of soil health indicators one and a half years after planting (October 2020) in Hawaiʻi. Points represent samples taken from subplots and are colored by treatment (agroforestry species mix). Red is a control plot where no agroforestry transition occurred. Green are erosion control treatment and blue are the early successional facilitation treatment. Abbreviations for indicator names are as follows: percarb (Total organic carbon), co2burst (24 hr CO2 burst), bglucosid ß-glucosidase), bglucosam (ß-glucosaminidase), pmn (Potentially mineralizable nitrogen), ph (pH), docdon (DOC:DON ratio), hwec (Hot water extractable carbon), whc (Water holding capacity), wsmegaa (Water stable mega-aggregates), bulkdens (Bulk density).

CARBON STORAGE:

We quantified the baseline carbon stocks in Puʻulani, which sets the stage for the first assessment of changes in carbon storage over time with agroforestry restoration. Results were published in the journal Agriculture in an article entitled: Assessing baseline carbon stocks for forest transitions: a case study from agroforestry restoration in Hawaiʻi. The abstract/summary and main figures of results can be found below.

ABSTRACT/SUMMARY:

As the extent of secondary forests continues to expand throughout the tropics, there is a growing need to better understand the ecosystem services, including carbon (C) storage provided by these ecosystems. Despite their spatial extent, there are limited data on how the ecosystem services provided by secondary forest may be enhanced through the restoration of both ecological and agroecological functions in these systems. This study quantifies the above- and below-ground C stocks in a non-native secondary forest in Hawaiʻi where a community-based non-profit seeks to restore a multi-strata agroforestry system for cultural and ecological benefits. For soil C, we use the equivalent soil mass method both to estimate stocks and examine spatial heterogeneity at high resolution (eg. sub 5 m) to define a method and sampling design that can be replicated to track changes in C stocks on-site and elsewhere. The assessed total ecosystem C was ~388.5 Mg C/ha. Carbon stock was highest in trees (~192.4 Mg C/ha; ~50% of total C); followed by soil (~136.4 Mg C/ha; ~35% of total C); roots (~52.7 Mg C/ha; ~14% of total C); and was lowest in coarse woody debris (~4.7 Mg C/ha; ~1% of total C) and litter (~2.3 Mg C/ha; <1% of total C). This work provides a baseline carbon assessment prior to agroforest restoration that will help to better quantify the contributions of secondary forest transitions and restoration efforts to state climate policy. In addition to the role of C sequestration in climate mitigation, we also highlight soil C as a critical metric of hybrid, people-centered restoration success given the role of soil organic matter in the production of a suite of on- and off-site ecosystem services closely linked to local sustainable development goals.

Figure 15a shows a depiction of Puʻulani and associated carbon pools prior to restoration with 100% non-native plant cover while 15b shows the vision of restoration to a multi-functional agroforest. In 2018, we measured the carbon storage in each of the following carbon pools: trees, woody debris, litter, roots, and soil. We will conduct another assessment 5-years after planting providing the first assessment of the impacts of agroforestry on carbon storage in Hawaiʻi.

Figure 15: (a) Current non-native forest at Puʻulani prior to agroforestry restoration along with measured carbon stocks (Mg C/ha) in vegetation and soil. The current forest is dominated by the non-native Java plum (Syzygium cumini) tree; (b) Envisioned restoration of Puʻulani with a diversity of culturally, ecologically, and economically valuable plant species, including overstory and mid-story species: koa (Acacia koa), pualoalo (Hibiscus arnottianus), loulu (Prichardia spp.), aʻaliʻi (Dodonaea vicosa), kukui (Aleurites moluccanus), iholena lele (Musa spp.) a Hawaiian variety of banana, as well as a variety of understory species including ilieʻe (Plumbago zeylanica), pohinahina (Vitex rotundifolia), nanea (Vigna mariana), ahuʻawa (Cyprus javanicus), and kupukupu (Nephrolepis cordifolia) [see Hastings et al. 2020 for details on restored scenario].

In terms of soil carbon, as expected, we found that percent carbon was highest in the top 0-20 cm and decreased with depth. The percent carbon also varied spatially, but was overall high (Figure 16).

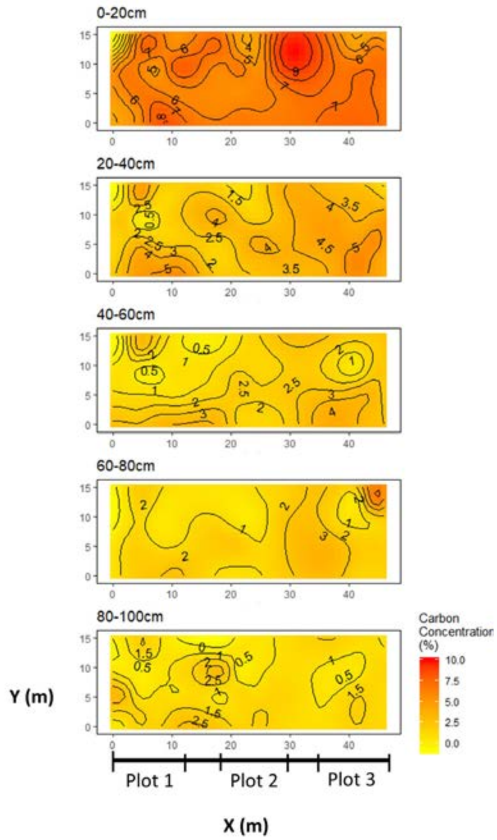

Figure 16: Interpolated contour maps of C concentration (% C) at each sampling depth demonstrating the lateral and vertical heterogeneity throughout the soil profile. (a) 0–20 cm; (b) 20–40 cm; (c) 40–60 cm; (d) 60–80 cm; (e) 80–100 cm. The y-axis is parallel to the slope of the ridge. The aspect of the slope 117° for plot 1 and 130° for plots 2 and 3.

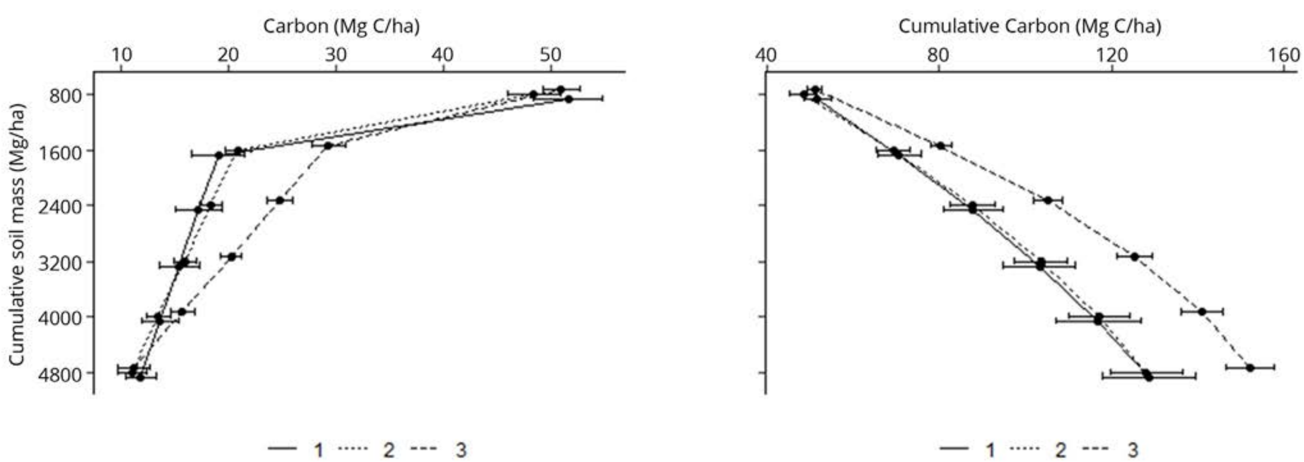

Figure 17: (a) Soil C stock (Mg C/ha) in each equivalent soil mass (ESM) increment of 800 Mg/ha and (b) cumulative soil C stock (Mg C/ha) for each plots. Points are plot means and error bars show ± one standard error.

Finally, we used the Equivalent Soil Mass method (Wendt and Hauser 2013) to quantify the total carbon from 0-100 cm (Figure 17). This method is seen as more robust than bulk density dependent methods and will allow us to quantify changes in soil C over time. Figure 18 shows the spatial distribution of soil C in the top 0-20 cm (ESM 800) and over the full profile.

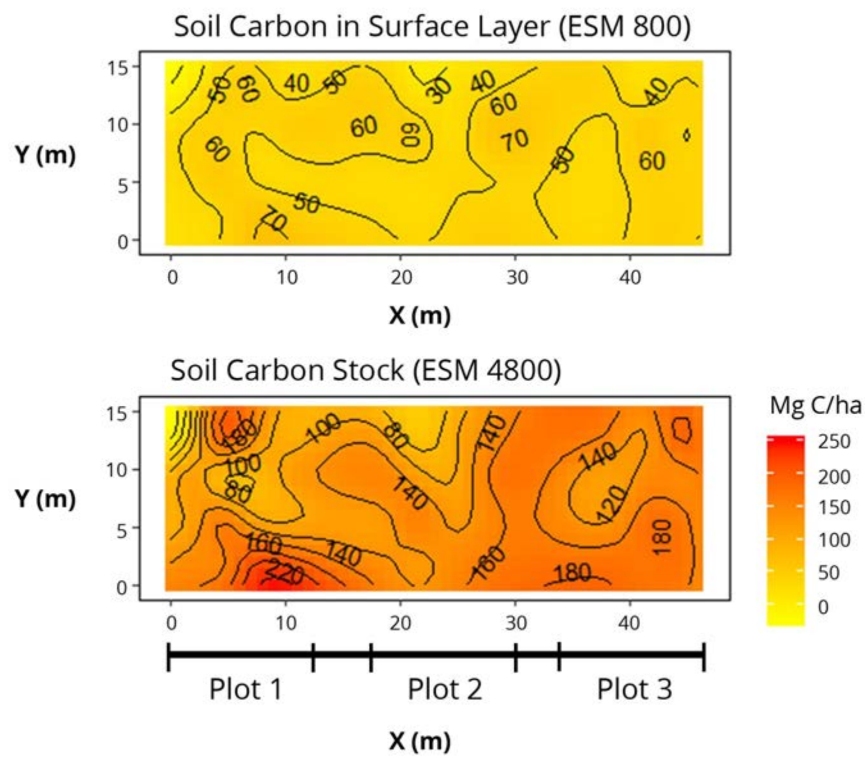

Figure 18: Interpolated soil C stock contour maps by Bayesian kriging of (a) surface soil C (Mg C/ha, ESM 800) and (b) deep soil C stock (Mg C/ha, ESM 4800). The y-axis is parallel to the slope of the ridge. The aspect of the slope is 117° for plot 1 and 130° for plots 2 and 3.

Objective 2: Synthesize existing evidence on the outcomes of agroforestry and create public/farmer outreach and training materials and a complementary peer-review publication.

Led by graduate student Zoe Hastings, our team successfully published an open-source peer-reviewed article on agroforestry, functional traits, and ecosystem services to the journal Conservation Science and Practice. We also published an article on the carbon baseline led by graduate student Angel Melone, and several more peer-reviewed articles are in progress. We also produced four fact sheets linking ecosystem services and agroforestry systems including: agroforestry and carbon sequestration; agroforestry and hydrologic services; agroforestry and climate regulation; and agroforestry and functional traits (see Appendix 1 for fact sheets). We additionally created a project brief and species cards describing the plants and their ecological, economic, and cultural value.

These publications have been distributed widely, including at our agroforest producer workshops (see objective 3).

Objective 3: Develop and pilot a 2-3 day workshop curriculum based on guidelines for agroforestry restoration using a functional trait approach to meet multiple food production, biodiversity, economic, and ecosystem service objectives.

We developed and carried out two workshops focused on agroforestry, ecosystem services, and functional traits, including one at Kākoʻo ʻŌiwi (Puʻulani) and one at Lonohana Estate's North Shore Farm. Given the evolving COVID-19 situation, we had to be flexible and adaptive, but we were pleased be able to carry out two very productive, in-person workshops. These workshops also responded to emerging consensus among agroforestry producers across the state for a need for opportunities for exchange with other producers. Curriculum maps and agendas are available from each workshop.

KĀKOʻO ʻŌIWI - OCTOBER 16, 2021

We had a fun and productive workshop at Kākoʻo ʻŌiwi focused on biocultural restoration, functional traits, and ecosystem services. See agenda here. In attendance were Kākoʻo ʻŌiwi staff (Mahealani Botelho and Kanekoa Kukea-Shultz), UH students and faculty (Leah Bremer, Clay Trauernicht, Zoe Hastings, Maile Wong, and Gina McGuire), Heʻeia NERR (Matthew Kahoʻohanohano), representatives from farms (6 participants) and from land trusts and educational institutions (2 participants), and NRCS (2 participants). The size was kept small given COVID restrictions, but we felt it provided an excellent opportunity for exchange. Figures 19 - 23 show images from the day.

The day included:

- Tour and discussion about Kākoʻo ʻŌiwi projects and kitchen facility for value-added products;
- Tour and discussion about Puʻulani agroforest areas along with the values and objectives of the project
- Discussion of successes and challenges at Puʻulani
- Outplanting of noni in a newly established agroforest plot
- Introduction to functional traits and ecosystem services in agroforestry design
- Introduction to biocultural restoration using a historical ecology approach
- Overview of incentives and other opportunities to work with NRCS
- Discussion of major challenges and opportunities facing agroforestry going forward.

As a summary of the workshop evaluation, all participants said they were "very likely" to use the information learned, with the exception of one who said they were "likely" to use the information. Participants were most positive about the opportunity to learn from and network with other ʻāina-based stewards, and suggested more time for planting and working in future workshops.

Figure 19: Learning from Kākoʻo ʻŌiwi Executive Director, Kanekoa Kukea-Shultz about the many projects Kākoʻo ʻŌiwi supports alongside their broader vision of restoring the ahupuaʻa.

Figure 20: Discussing Puʻulani agroforestry design, successes, and challenges.

Figure 21: NRCS supporters provide insight into agroforest planning and strategies to collaborate with NRCS for farms like Kākoʻo ʻŌiwi.

Figure 22: Zoe Hastings provides an introduction to functional traits in agroforestry design.

Figure 23: He'eia NERR graduate student, Matt Kaho'ohanohano provides an intro and discussion into biocultural restoration using a functional trait approach.

LONOHANA ESTATE'S NORTH SHORE FARM - OCTOBER 23, 2021

The workshop at Lonohana Estate's North Shore Farm focused on the best practices for cacao establishment and participants were able to see cacao, windbreaks, and shade trees in different stages of growth from saplings to over 10 years old. See agenda here. In attendance were Lonohana staff (Seneca Klassen and Carly Miller), a UH student (Zoe Hastings), O'ahu RC&D staff (Dave Elliot, Logan Motas, and India Clark), a nursery person (Ben Fields), NRCS (1 participant), and land managers, farmers, and technical service providers (15 participants). Due to COVID-19 restrictions, we had to limit the size of the event, but it was still an excellent opportunity for exchange between many experienced farmers, land managers, and technical support providers. Figures 24 - 28 show images from the day.

The day included:

- Lecture on best practices for cacao establishment
- Overview of top recommended species for windbreaks and shade
- Successional shade strategy - learning about the importance of tree cages for establishment and how to install them
- Overview of incentives and other opportunities to work with NRCS
- Tour of cacao blocks in different stages of establishment
- Discussion on the role of different species for wind/shade protection, their pros and cons, and the stages of cacao development
- Discussion on post-harvest handling of cacao and economies of scale needed for fermentation

Ten participants said they were “very likely” to use the information learned, and four said they were “likely” to use the information. Participants were most positive about the opportunity to network with each other, learn from people more experienced in cacao agroforestry, and engage in hands-on learning.

Figure 24: NRCS forester Matt Cocking and O’ahu RC&D director Dave Elliot confer on planting layout, while other participants plant windbreak and cacao trees and install cages as part of an activity to learn about successional shade strategies.

Figure 25: Seneca Klassen of Lonohana Estate explains how agroforestry supports the ecological and economic resilience of his farm and vertically integrated value-added business.

Figure 26: Participants walk past blocks of cacao trees with interspersed shade trees and rows of windbreak trees between the blocks.

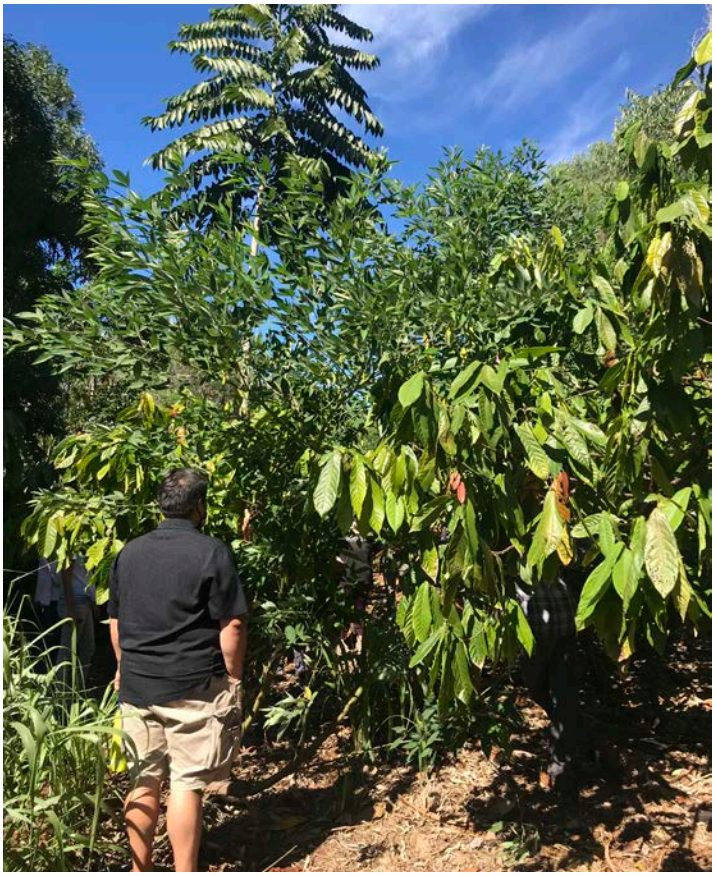

Figure 27: A participant observes pigeon pea, an important successional shade plant in the establishment phase, at the end of its functional life in the cacao agroforest. Beyond, a later successional shade tree emerges from the cacao canopy.

Figure 28: Participants of the workshop gather under the canopy of the cacao agroforest.

SUMMARY OF DELIVERABLES:

1. Restoration plan and long-term monitoring protocol for Kako'o 'Ōiwi.
    a. See objective 1 - completed May 2022
2. 10 demonstration agroforestry plots established, managed, and maintained.
    a. See objective 1 - completed June 2019
3. Public/farmer outreach publication and training materials produced
    a. See objective 2 - completed October 2021
4. Training materials based on species composition and spacing to implement and manage agroforestry created. Includes photos of relevant species in different functional trait groups
    a. See objective 2 and 3 - this was completed as fact sheets, a project brief, and species cards - completed October 2021

5. Peer-review publication synthesizing evidence base of agroforestry in the Pacific and tropics

    a. Completed, but as agreed, we published 2 peer-reviewed articles, one on agroforestry design using functional traits and one on carbon storage - completed January 2021

6. Monitoring infrastructure and datalogging to streamline monitoring of agroforest outcomes

    a. Completed, see objective 1 - completed May 2022

7. Workshop curriculum and pilot workshop session to disseminate training materials

    a. Completed, see objective 3 - completed October 2021

8. Participation in public event to share how innovation will result in improved conservation.

    a. Completed, see objective 3. We also held over 20 community work days at the site as part of management and education - completed October 2021

9. Presentation of project at Hawai'i Conservation Conference 2019, 2020, and 2021.

    a. Completed - team members and students Zoe Hastings, Maile Wong, Angel Melone, and Matthew Kahoʻohanohano all presented in one or two conferences - completed July 2021

10. Final fact sheet for public use on technical aspects of project.

    a. Completed - see objective 2 - completed October 2021

11. Final technical report for NRCS.

    a. This report - completed May 2022

12. Provide a minimum 1-hour PowerPoint presentation of the project's accomplishments either live or in a teleconference/webinar with the NRCS PIA State Office in Honolulu to share the final products

    a. To be completed by August 2022

Supplementary Table 1: Description of NRCS Mixed Agroforestry Technical note guidelines and how the design at Puʻulani followed these guidelines.

Requirement	Puʻulani
Mixed Agroforests are closed-canopy forests that contain a collection of plants representing high diversity in species, canopy structure and arrangement with the following intent relating to NRCS planning & assistance	Total of 30 species intentionally planted, represents high species diversity and canopy structure (low, mid, upper story); will be closed canopy forest
The principal purpose of Mixed Agroforests is to provide common forest ecosystem services by addressing resource concerns for inadequate forest structure or composition, excessive plant pest pressure, sheet & till erosion, improving water quality (sediments, nutrients), and increasing carbon sequestration.	Species selected for ecosystem service traits including sediment and nutrient retention, resilience, succession, and carbon sequestration. Demonstration undergoing monitoring to evaluate these linkages in greater detail.

Mixed Agroforests are not commercial production systems and require much lower levels of management and inputs than cropland systems, including commercial orchards.	Focused on species for farm and community use; the high diversity system at Pu'ulani will require less inputs than intensive production system due to beneficial insects, leaf litter accumulation, etc.
1a. Planned Mixed Agroforests shall be designated as Forest land use.	Pu'ulani focused on forest land use
1b. The Wildlife land use modifier can be designated only if the post-implementation native plant count exceeds 80% for tall stature trees and 80% for short-stature trees &shrubs.	N/A
1c. Crop, Pasture, Range, Associated Agricultural Lands or weedy fallow lands can be converted to Mixed Agroforests	Pu'ulani was non-native forest, abandoned pasture
1d. Existing forests containing at least a 20% native tree/ shrub count for all plants > 4.5 feet tall shall not be converted to Mixed Agroforests.	Pu'ulani was non-native forest
1e. Existing forests that have less than a 20% native tree/ shrub count for all plants > 4.5 feet tall may be converted to Mixed Agroforests, but all native plants must be retained as part of the planned agroforest during site preparation work.	Pu'ulani was non-native forest
2a. Must contain six or more tree/shrub genera based on planned acres (Table 1). Refer to the PIA Vegetation Specification for species recommendations.	More than 30 genera are planted over 1/2 acre, greatly exceeding table 1 guidelines.
2b. For each plant genus/species that produces NTFP only: Planting in pure or contiguous clumps or rows is limited to five (5) plants for tall stature trees or 20 plants for short stature trees/shrubs (Table 3) to ensure highly mixed planting arrangements.	No NTFP species are planted in pure or contiguous clumps or rows - species are mixed together in alternating arrangements.
2c. Post-implementation tree/shrub counts (pre-existing + planted) must be at least 425 plants per acre: i. At least 25 plants per acre must be tall stature trees (25-50 is typical). ii. The balance must be short-stature trees or shrubs. This count can include high percentages of species established via cuttings (Table 2), and coppice-managed as sources of mulch for weed control & nutrient cycling, fodder or N-fixation.	Over 2000 plants in 1/2 acre. 178 trees (tall stature) and 820 shrubs, all carefully selected for ecosystem services
3a. Native trees/shrubs will comprise at least 20% of the post-implementation tree/shrub plant count, including pre-existing plants. Such plants can provide NTFP but would not be counted under item 3.b below.	Native trees/shrubs comprise 61% of the post-implementation tree/shrub count.

3b. Non-native species that produce NTFP (Table 3): i. Shall not exceed 50% of the post-implementation tree/ shrub plant count. ii. The quantity of each NTFP-producing genus/species will not exceed the amounts provided in Table 3.	Non-native and polynesian introduced NTFP species are 38% of the post- implementation tree/shrubs plant count; the numbers in Table 3 are not exceeded for those included in Puʻulani (counts are less than 15 of each mountain apple, breadfruit, and mango and less than 50 of each banana and plumeria)
3c. After meeting the requirements of items 3.a and 3.b above, other non-native trees/shrubs (including timber-producing trees) can be included as the remaining balance of the planting plan.	Only one of the non-native trees/shrubs is non NTFP-producing (Big Leaf Mahogany for timber)
3d. Tree/shrub species selected for Mixed Agroforests must have lifespans of at least 15 years. Any pruning or harvesting of NTFP will not destroy these plants during the 15- year practice lifespan.	Requirement met

Supplementary Table 2: Species and number of individuals planted at Puʻulani in 2019 and their contemporary non-timber forest product use. Species' origins include native (*), polynesian (⁺), and introduced.

Name	Species	Contemporary NTFP Use	Number planted
Mai'a iholena lele⁺	*Musa sp.*	food	40
Guava	*Psidium guajava*	food	5
Aweoweo*	*Chenopodium oahuense*	ceremony	85
Māmaki*	*Pipturus albidus*	tea, medicine	100
'Awa⁺	*Piper methisticum*	drink, ceremony, medicine	100
Pohinahina*	*Vitex rotundifolia*	lei, hula, medicine	130
Pualoalo*	*Hibiscus arnottianus*	lei	85
A'ali'i*	*Dodonaea viscosa*	lei, hula, medicine	100
Alahe'e*	*Psydrax odorata*	lei	20
Maile*	*Alyxia stellata*	lei	100
'Ulu⁺	*Artocarpus altilus*	food	10
'Ohi'a 'ai⁺	*Syzigium malaccense*	food	5
Mango	*Mangifera indica*	food	1
Kukui⁺	*Aleurites moluccanus*	food, medicine, lei, hula, ceremony	2
Kamani⁺	*Calophyllum inophyllum*	food	5
Plumeria	*Plumeria spp.*	lei	5
'Ohi'a lehua - ahihi*	*Metrosideros tremuloides*	lei, hula, ceremony	40
'Ohi'a lehua - embricada*	*Metrosideros polymorpha*	lei, hula, ceremony	10
'Ohi'a lehua - mamo*	*Metrosideros polymorpha*	lei, hula, ceremony	20
Koa*	*Acacia koa*	lei, wood products	20
Big Leaf Mahogany	*Swietenia macrophylla*	wind break, wood (selective harvest)	60

Loulu*	*Pritchardia hillebrandii*	building material - roof thatching	20
Wiliwili*	*Erythrina sandwichensis*	lei	10
Kā'e'e (Sea Bean)*	*Mucuna gigantea*	lei	10
Kalo (Taro)+	*Colocasia esculenta*	food	10
Ho'io	*Anthyrium spp.*	food	200
Ahu'awa*	*Cyperus javanicus*	awa preparation	200
Palapalai*	*Microlepia strigosa*	lei, hula	500
Kupukupu*	*Nephrolepis cordifolia*	lei, hula	150
Nanea*	*Vigna marina*	lei	200
Uhaloa*	*Waltheria indica*	medicine	50
Vetiver	*Chrysopogon zizanioides*	medicine	30
Comfrey	*Symphytum officinale*	medicine	100
'Aki'aki*	*Sporobolus virginicus*		200
Ilie'e*	*Plumbago zeylanica*		100