UNDERSTANDING THE POTENTIAL FOR RESTORATION THROUGH AGROFORESTRY IN HAWAIʻI

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This dissertation is dedicated to my parents, Angela and Tim Hastings.
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ABSTRACT

Agriculture is a major driver of global environmental change. Restorative practices like agroforestry, that integrate native and non-native, culturally important plants while mimicking the structure and function of native forests have the potential to increase biodiversity and ecosystem services of conventionally managed and fallow agricultural lands. However, what the potential is of restoring these lands using agroforestry and who is able to participate in agroforestry transitions remains a question. I focus on agroforestry transitions in Hawai‘i, where a long history of Indigenous agroforestry and more recent interest in biocultural restoration provide an important context for understanding equitable pathways to agroforestry today. In the first chapter, I show how integrating co-production of knowledge with functional trait approaches to designing restoration and agroforestry research with local stakeholders can lead to more inclusive and scalable results. In the second chapter, I apply this approach to an experimental restoration that asks, 1) do initial measures of restoration success (i.e., understory composition, understory cover, and mid- and over-story survival) vary between treatments over the first two years, and if so, are these treatment effects mediated by other drivers, and 2) how does the ecological condition of the site compare to pre-restoration? Based on plant community metrics, the results show that non-native forests have a high potential for restoration through agroforestry, and this provides an important first step in documenting what non-native forest to agroforest transitions can look like. The third chapter is a state-wide study, in which I ask, what factors drive and/or restrain transitions to agroforestry, and who is able to participate? I found that agroforestry practitioners are motivated to restore ecosystems and reclaim sovereignty, not just by the direct or practical benefits of agroforestry. Practitioners’ values often conflict with the values of dominant funders, landowners, and other institutions, which produces unique obstacles. Access to off-site resources that are inequitably distributed often determines who can persist despite the obstacles. Taken together, the findings in this dissertation highlight the significant opportunity to restore conventionally managed and fallow agricultural lands through agroforestry and the need for structural change to ensure equitable access to the opportunity presented by these land use transitions.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................................................ ii
ABSTRACT ............................................................................................................................................................ v
LIST OF TABLES ................................................................................................................................................. viii
LIST OF FIGURES ................................................................................................................................................ ix
LIST OF APPENDICES ........................................................................................................................................ x
CHAPTER 1. INTRODUCTION ............................................................................................................................ 1
  Goals of the dissertation ................................................................................................................................. 3
  Outline of the dissertation ............................................................................................................................... 3
  References ......................................................................................................................................................... 5

CHAPTER 2. INTEGRATING CO-PRODUCTION AND FUNCTIONAL TRAIT APPROACHES FOR INCLUSIVE AND SCALABLE AGROFORESTRY SOLUTIONS ...... 9
  Abstract ......................................................................................................................................................... 9
  Introduction ................................................................................................................................................... 10
  Co-production and functional trait-based approaches ................................................................................ 13
  Case study ................................................................................................................................................... 13
    Restoration Site ........................................................................................................................................ 13
    Co-design, trait-based approach Part I: Project visioning ........................................................................ 14
    Co-design, trait-based approach Part II: Trait data collection and analysis ......................................... 16
    Co-design, trait-based approach Part III: Participatory species selection ............................................ 18
  Benefits, challenges, and applications of an integrated approach .......................................................... 19
  References ................................................................................................................................................... 22

CHAPTER 3. NON-NATIVE FORESTS HOLD HIGH POTENTIAL FOR RESTORATION THROUGH AGROFORESTRY IN A PACIFIC ISLAND ECOSYSTEM ........................................... 27
  Abstract ....................................................................................................................................................... 27
  Introduction .................................................................................................................................................. 29
  Methods ....................................................................................................................................................... 31
    Study Site ................................................................................................................................................ 31
    Experimental Design ............................................................................................................................... 33
    Data collection and analysis ................................................................................................................... 34
  Results ......................................................................................................................................................... 37
    Effect of treatment on restoration success ............................................................................................. 37
Comparison of restoration treatments to the baseline non-native forest .............................................. 40
Discussion ............................................................................................................................................ 42
Data availability statement .................................................................................................................. 46
Appendix 3.1 ....................................................................................................................................... 47
Appendix 3.2 ....................................................................................................................................... 49
Appendix 3.3 ....................................................................................................................................... 50
Appendix 3.4 ....................................................................................................................................... 51
References .......................................................................................................................................... 55

CHAPTER 4. WHO GETS TO ADOPT? CONTESTED VALUES CONSTRAIN JUST TRANSITIONS TO AGROFORESTRY ......................................................... 60
Abstract ............................................................................................................................................ 60
Introduction ....................................................................................................................................... 62
Methods ............................................................................................................................................ 65
  Sampling Frame ............................................................................................................................... 65
  Interviews and Focus Group .......................................................................................................... 66
Results ............................................................................................................................................... 67
  Agroforestry practices and practitioners are diverse ...................................................................... 67
  Motivations relate to practitioners’ values and the direct benefits of agroforestry .................... 69
  Agroforestry practitioners face common and unique constraints ............................................ 77
  Access to external resources shapes who gets to practice agroforestry .................................... 85
Discussion ....................................................................................................................................... 90
  Practitioners transition to agroforestry to restore ecosystems and reclaim sovereignty .......... 93
  The term agroforestry is both unifying and exclusionary ............................................................. 94
  Structural change is needed for agroforestry transitions to be just ........................................... 94
Conclusion ....................................................................................................................................... 97
References ....................................................................................................................................... 99
Appendix 4.1 ....................................................................................................................................... 106
Appendix 4.2 ....................................................................................................................................... 107

CHAPTER 5. CONCLUSION ............................................................................................................. 110
Synthesis of findings ......................................................................................................................... 110
Management recommendations ....................................................................................................... 111
Limitations ....................................................................................................................................... 112
Opportunities for future research .................................................................................................. 113
LIST OF TABLES

Table 2.1. Functional traits predicted to influence the rates of ecological processes ..........17
Table 2.2. Species selected through a co-design, functional trait approach......................18
Table 2.3. Benefits of integrating co-production and trait-based approaches..................19
Table 3.1. Summary of plant community characteristics pre- and post-restoration ..........37
Table 4.1. Factors motivating people to transition to agroforestry in Hawai‘i ..................71
Table 4.2. Agroforestry-specific obstacles that practitioners in Hawai‘i face .....................80
Table 4.3. Factors influencing practitioners’ ability to participate in agroforestry transitions in Hawai‘i ...........................................................................................................................................86
LIST OF FIGURES

Figure 2.1. Comparison of the ecosystem restoration and diversified agriculture continuums...11
Figure 2.2. Steps in an integrated approach to research design ....................................................15
Figure 3.1. Map of the study area in Heʻeia, Oʻahu, Hawaiʻi..........................................................32
Figure 3.2. Structural equation models of drivers of agroforestry understory cover ..................36
Figure 3.3. Regressions of predictors of understory cover of agroforestry species ...................38
Figure 3.4. Survival rates for species and treatments .....................................................................40
Figure 3.5. Photographs of the study site pre- and post-restoration ............................................41
Figure 3.6. Non-metric multidimensional scaling understory plant composition before and after restoration ......................................................................................................................................42
Figure 4.1. Photograph of a multi-story agroforestry system in Hawaiʻi ....................................69
Figure 4.2. Motivators and obstacles to agroforestry transitions in Hawaiʻi..............................78
Figure 4.3. Artwork illustrating key themes of agroforestry interviews.........................................92
LIST OF APPENDICES

Appendix 3.1. List of plant species present pre-restoration..........................................................47
Appendix 3.2. Lists of species in each agroforestry treatment..........................................................49
Appendix 3.3. Parameter estimates from the best-fit structural equation model..............................50
Appendix 3.4. Soil health analyses ..................................................................................................51
Appendix 4.1. Human Studies Program Institutional Review Board approval letter .......................106
Appendix 4.2. Semi-structured interview guide ..............................................................................107
CHAPTER 1. INTRODUCTION

Unprecedented conversion of native ecosystems to intensive agricultural systems (IPBES, 2018) has prompted parallel calls for forest restoration and regenerative agriculture, including the designation of the United Nations “Decade on Ecosystem Restoration” (UNEA, 2019). Restorative practices like agroforestry, that mimic the structure and function of native forests using native and non-native, culturally important plants, have the potential to simultaneously meet both forest restoration and regenerative agriculture goals when applied to conventionally managed and fallow agricultural lands. As a result, institutions ranging from local governments to international agreements are increasingly including agroforestry as a component of their social-ecological resilience strategies (Rosenstock et al., 2019; Griscom et al., 2020), including National Adaptation Plans and Nationally Declared Contributions (Fortuna et al., 2019; Meybeck et al., 2019).

Yet, how to increase agroforestry on landscapes to meet these targets remains a question. Some of the challenges to increasing agroforestry implementation is discrepancy in conceptualizations of what agroforestry is. The term agroforestry was coined in the late 1970’s by researchers and development professionals, primarily from high-income countries, to describe land management systems that simultaneously increase the productivity of landscapes while also reducing environmental degradation (Bene et al., 1977). Agroforestry in these early conceptualizations was seen as a means to achieving a productive farm, which is still the case in many contexts, especially resource-poor farms (Suryanata, 2017). However, the goals and conceptualizations of agroforestry practices vary in different contexts. Landscapes managed using agroforestry practices can also be seen as the goal itself. Today, agroforestry has come to encompass farm-level technical practices that integrate woody plants and crops and/or livestock for environmental and practical benefits (NRCS, 2013), Indigenous stewardship practices based in ecomimicry (Ticktin et al., 2018; Winter et al., 2020), and a landscape approach “to removing the conceptual and institutional barriers between agriculture and forestry” (van Noordwijk et al., 2018).

Early research on agroforestry led to a large body of literature documenting the ecosystem services of agroforestry systems and optimizing system design for both production and environmental benefits. In 1978, the International Council for Research on Agroforestry...
(ICRAF; renamed the World Agroforestry Centre in 2002) was established to support and coordinate research on agroforestry (Suryanata, 2017). Research has since shown forms of agroforestry can diversify livelihoods (Miccolis et al., 2019), conserve biodiversity (Kremen and Merenlender, 2018), and increase pollination services (Bentrup et al., 2019), sediment retention, and nutrient cycling (Torralba et al., 2018). Agroforestry is considered a natural climate solution (Griscom et al., 2017) as these practices also contribute to carbon sequestration (Chapman et al., 2020) and social-ecological resilience (Quandt et al., 2017; Ticktin et al., 2018), which is the ability of a system to continue to function over time despite disturbances (Berkes et al., 2002).

Although the above research, as well as research on agroforestry adoption (e.g., Pattanayak et al., 2003; Mercer, 2004; Glover et al., 2013), is important for understanding and promoting agroforestry transitions, much of the literature neglects the unequal power dynamics shaping who is able to participate in transitions. For example, focusing on the experience of individual landowners can downplay the power relations that shape who can be a land manager and assumes that all farmers have the power to choose sustainable forms of agriculture (Calo, 2020). Considering the institutional and social factors that influence agroforestry transitions remains a major gap (Rocheleau, 1998; Molina, 2013; Meek, 2016; Ollinaho and Kröger, 2021). Overall, understanding what the potential is of restoring agricultural lands using agroforestry, and who is able to participate in agroforestry transitions, is critical to designing place-based interventions that lead to meaningful and lasting land-use change.

This study focuses on agroforestry transitions in Hawai‘i where a long history of Indigenous agroforestry and interest in biocultural restoration provide an important context for understanding equitable pathways to agroforestry today. Indigenous agroforestry was widespread in Hawai‘i for nearly a millennia prior to European colonization, covering an estimated 34.7% (34,907 hectares) of Indigenous agricultural lands (Kurashima et al., 2019). Indigenous agroforestry was characterized by a diversity of perennial understory and tree crops that were used for food, medicine, ceremony, tools, clothing, and building (Kurashima and Kirch, 2011; Lincoln, 2020). Yet, following European contact in 1778, the Kānaka ʻŌiwi (Native Hawaiian) population declined an estimated 84% by 1840 (Swanson, 2016). In 1848, a process called the Māhele (division of land), led to land privatization and accumulation by non-Hawaiians (Kameʻeleihiwa, 1992). Sugar and pineapple plantations came to dominate the agricultural and political landscape, and, in 1893, a group of American-backed white businessmen overthrew the
Hawaiian monarchy (Kameʻeleihiwa, 1992). As a result, today Hawaiʻi for the most part lacks a tradition of smallholder farms growing diversified crops (Suryanata et al., 2021).

This legacy combined with the high costs of land, labor, water, and other infrastructure significantly impedes the regeneration of diversified agriculture in Hawaiʻi (Suryanata, 2002; Heavivilin and Miles, 2018). Now, an estimated 40% of agricultural lands are fallow (Melrose et al., 2015), less than 8% of the state’s agricultural zoned lands are used for growing crops, most products are exported (Melrose et al., 2015; USDA-NASS, 2019), and nearly 88% of food is imported (Loke and Leung, 2013). In response, the state department of forestry, state resilience office, and other public and private institutions have included agroforestry in their resilience strategies, and public discourse in support of agroforestry as a multi-benefit solution is building (Caulfield, 2019). This social-ecological context makes Hawaiʻi an especially important case study for understanding the potential for, and dynamics of, agroforestry transitions today.

GOALS OF THE DISSERTATION

The overarching goal of this dissertation is to support the biocultural restoration of fallow and conventional agricultural land in a way that is socially just and social-ecologically resilient. Given the gaps in our knowledge of transitions to agroforestry as a form of ecological or biocultural restoration today, the goals of this study are to 1) advance participatory and ecological research methods for agroforestry transitions so that results are more inclusive and scalable, 2) better understand how agroforestry species mixes affect restoration outcomes in the early stages of establishment, 3) better understand the main motivations and challenges of agroforestry practitioners and the conditions that allow them to persist.

OUTLINE OF THE DISSERTATION

Chapters 2 and 3 present a site-level case study carried out in collaboration with Kākoʻo ʻŌiwi, a community-based non-profit organization in Heʻeia, Oʻahu, Hawaiʻi. In Chapter 2, I present a method to select species for agroforestry research that integrates two well-established research approaches: co-production of knowledge and functional trait-based design. I illustrate this integrated approach through an agroforestry design case study at a restoration site in Heʻeia.

In Chapter 3, I present results of the first two years of the restoration in Heʻeia. I asked, 1) do initial measures of restoration success (i.e., understory composition, understory cover, and
mid- and over-story survival) vary between treatments over the first two years, and if so, are these treatment effects mediated by other drivers, and 2) how does the ecological condition of the site compare to pre-restoration? We found that restoration success did not differ between treatments in the first two years of restoration, but that compared to pre-restoration, forest structure, species composition, and the number of people engaged at the site changed. Taken together our findings suggest that non-native forests on agricultural fallows have a high potential for restoration through agroforestry. This chapter provides an important first step in documenting what non-native forest to agroforest transitions can look like and what their potential is.

In Chapter 4, I present a state-level study that investigated the questions, what factors drive and/or restrain transitions to agroforestry and who is able to participate? I interviewed 38 agroforestry practitioners across five main islands of Hawai‘i and analyzed the data using constructivist grounded theory. I found that agroforestry practitioners face a similar suite of structural obstacles as other agricultural producers; however, the conflict in values between agroforestry practitioners and dominant institutions manifests as four additional dimensions of obstacles constraining agroforestry transitions. Who is able to practice despite these obstacles is tightly linked with people’s ability to access off-site resources that are inequitably distributed. I discuss potential solutions in the context of Hawai‘i and provide transferrable principles and actionable strategies for achieving equity in agroforestry transitions.

In Chapter 5, I present a synthesis of Chapters 2-4 and offer potential directions for future interdisciplinary, action-oriented research that builds on this study.
REFERENCES


ABSTRACT

Calls for, and commitments to, forest restoration and regenerative agriculture are booming. While these practices are often conceptualized and implemented separately, in many contexts, research and practice at the intersection of forest restoration and diversified agriculture can accelerate the mutual goal of increasing biodiversity and ecosystem services on degraded lands. However, research on integrated forest-agriculture practices, or agroforestry, often leaves out locally important native species and produces findings that are species-specific, which together constrain research-practice connections. We discuss a research design process that integrates two well-established methods and allows for local customization in species selection, while also enabling study findings to be generalized to other sites. We illustrate this process through a case study from Hawai‘i and discuss the benefits, challenges, and potential further applications.
INTRODUCTION

Unprecedented conversion of native ecosystems to intensive agriculture (Montanarella, Scholes, & Brainich, 2018) has prompted parallel calls for forest restoration and regenerative agriculture, including the designation of the United Nations “Decade on Ecosystem Restoration” (UNEA, 2019). While some argue current levels of evidence-based science are insufficient to translate the UN call into meaningful conservation gains (Cooke, Bennett, & Jones, 2019), the designation may provide a critical incentive to improve shortcomings and broaden the scope of restoration (Young & Schwartz, 2019). Debate around how to implement restoration has led to the development of restoration principles that are inclusive of multiple goals (Gann et al., 2019; Suding et al., 2015). The restorative continuum includes diversified agricultural practices as remediating activities (Gann et al., 2019); however, deep seated conceptualizations of forest and agriculture as separate often preclude meaningful intersections (Chazdon et al., 2016).

Yet, side-by-side comparison of the ecosystem restoration and diversified agriculture continuums highlights important forest-agriculture intersections (Fig. 2.1). Agroforestry encompasses a spectrum of practices that integrate trees with tended and harvested plants or animals. These linked human-natural systems (Liu et al., 2007) contribute to social-ecological resilience (Ticktin et al., 2018) and are often based on customary knowledge-practice-belief systems developed through adaptive processes and transmitted over generations (i.e., indigenous and local knowledge; Berkes, 2008). When applied in a restoration context, agroforestry practices are often called hybrid restoration (Burnett et al., 2019; Hobbs et al., 2014), and fit under the umbrellas of the restorative continuum (Gann et al., 2019) and forest landscape restoration (Mansourian et al., 2020).
Figure 2.1. Ecosystem restoration and diversified agriculture are often conceptualized separately. However, in certain contexts, the intersection of these two concepts (green square) holds the most potential for increasing biodiversity, ecosystem services, and human well-being. Practices at this intersection are often called agroforestry or hybrid restoration (Hobbs et al., 2014; Burnett et al., 2019). Placement of diversified agriculture practices along the restorative continuum varies with implementation (e.g., alley cropping that includes native plants could be considered “initiating native recovery”). The ecosystem restoration continuum is modified from Gann et al. (2019).

Integrated forest-agriculture practices can accelerate the cross-sectoral goal of restoring biodiversity and ecosystem services. A key advantage of integrating agricultural production in forest restoration is the ability to offset planting and maintenance costs with crop and non-timber forest product sales (Vieira, Holl, & Peneireiro, 2009). Including crops in restoration can also improve livelihoods (Miccolis, Peneireiro, Vieira, Marques, & Hoffmann, 2019) and broaden restoration to contexts where conventional restoration may be difficult or impractical (Park, Turner, & Higgs, 2018). Similarly, increasing plant diversity on farms can increase a suite of ecosystem services such as pollination (Bentrup, Hopwood, Adamson, & Vaughan, 2019; Guzman, Chase, & Kremen, 2019; Kremen & M’Gonigle, 2015), cultural services (Brandt,
(Zimmermann, Hensen, Mariscal Castro, & Rist, 2012), carbon sequestration (De Stefano & Jacobson, 2018), and sediment retention (Jose, 2009).

Despite evidence of the benefits of restorative forest-agriculture practices, the applicability of this research is often constrained by the underrepresentation of locally important native species and compounded by species-specific study findings. Much of the global agroforestry research agenda has focused on a limited number of species and specific commodity crops (Wolz & DeLucia, 2018). Many farmers and communities, however, are interested in growing and using other species, and the dearth of research including locally appropriate species may constrain agroforestry establishment globally (Dumont et al., 2019). This is especially true for many native plants that produce non-timber forest products, which traditionally may have been actively managed to increase production, but not necessarily planted to restore populations (e.g., de Oliveira & Carvalhaes, 2016). Traditionally farmers established hybrid systems within existing native forests by selectively thinning trees to create light for harvested understory plants or animal forage while retaining culturally important trees, for example in the case of oak trees (Quercus sp.) and pigs in Europe (Dupraz & Newman, 1997) and ʻōhiʻa lehua trees (Metrosideros polymorpha) and medicinal plants in Hawaiʻi (Quintus et al., 2019). Now, more commonly, farmers start with cleared agricultural fields or secondary forests where many native, culturally important plants no longer occur. Not only are these species largely ignored in research contexts, but often study designs tie findings to species identities, further limiting scalability (Coe et al., 2014).

Thus, a critical challenge is how to improve the design of agroforestry and restoration research so that studies are both inclusive of local needs and produce findings useful to other sites. Multi-criteria species selection tools for restoration and agroforestry establishment (e.g., Meli, Martínez-Ramos, Rey-Benayas, & Carabias, 2014; Reubens et al., 2011) are valuable; however, they are infrequently operationalized in a research design context. In this paper, we discuss a process for designing research in a way that is customizable and generalizable that integrates two well-established approaches: co-production and functional trait-based design. We use a case study from Hawaiʻi to illustrate this process and the benefits and challenges. While this approach is particularly relevant to agroforestry and hybrid restoration, it is also applicable to any restoration or diversified agriculture intervention.
CO-PRODUCTION AND FUNCTIONAL TRAIT-BASED APPROACHES

Co-production of knowledge is a well-established strategy for focusing research on local priorities, including locally important taxa. Co-production, like participatory action and community-based research, is a process for bringing together diverse groups of scientists and practitioners to iteratively create new knowledge and practice (Norström et al., 2020). While co-production has a long history in agriculture research (e.g., Rocheleau, 1991; Scoones & Thompson, 1994), application of this approach is relatively sparse in native ecosystem restoration research (Derak, Cortina, Taiqui, & Aledo, 2018; Lazos-Chavero et al., 2016).

Practicing co-production in a restoration context, however, can improve implementation. Producer participation from the onset of the research process leads to higher engagement and improved outcomes (Méndez, Caswell, Gliessman, & Cohen, 2017), although practitioner participation levels vary (Lacombe, Couix, & Hazard, 2018). While co-production is not appropriate or effective in all situations (Lemos et al., 2018), its application to co-designing interventions with practitioners can create more inclusive designs (Dumont et al., 2019).

Ecologists are transitioning to functional trait-based studies, which can help move beyond species-specific findings and thereby improve the generalizability of research across sites. Functional traits, or characteristics of an organism that influence their response to or effect on their environment, such as rooting depth, may be an effective tool for understanding the relationship between biodiversity and ecosystem services (Naeem & Wright, 2003). According to functional trait theory, a species' traits reflect the species' resource and life-history trade-offs (Reich, 2014), and they vary continuously along resource availability gradients in predictable ways (Lavorel, 2013). A functional trait approach to species selection uses plant trait data to predict species mixes that are most likely to affect the rates of certain ecological processes (Cordell, Ostertag, Michaud, & Warman, 2016). A functional trait approach to design has been applied to native forest restoration (Ostertag, Warman, Cordell, & Vitousek, 2015; Werden et al., 2018) and proposed for the study of agrobiodiversity (Laughlin, 2014; Wood et al., 2015).

CASE STUDY
Restoration Site

He‘eia, Hawai‘i is an ahupua‘a (traditional Hawaiian political-ecological land division) on the island of O‘ahu. Here, several non-governmental organizations are restoring biodiversity
and ecosystem services through traditional management practices including agroforestry, wetland taro (lo‘i kalo, *Colocasia esculenta*), and wetland and marine fish ponds (loko i‘a). He‘eia was recently designated a National Estuarine Research Reserve (NERR), the first to emphasize social-ecological systems management with a primary objective to understand how the mutually reinforcing restoration of land and culture (biocultural restoration; Kimmerer, 2011) influences ecosystem services (Hawai‘i Office of Planning, 2016).

The design process case study focused on a ~4,000m² ridge stewarded by Kāko‘o ‘Ōiwi, a community-based non-profit farm whose mission is “to perpetuate the cultural and spiritual practices of Native Hawaiians”. Prior to European contact (1778) and until the mid-1800s, the land was farmed by Kānaka Maoli (Indigenous Hawaiians) who tended kalo, other crops, and native plants. Colonization displaced local families, and the land transitioned to sugarcane, pineapple, rice, and cattle. The ridge has now been fallow for at least 70 years and is part of a 164 hectare parcel that Kāko‘o ‘Ōiwi leases from the Hawai‘i Community Development Authority. The vegetation is almost entirely non-native, with a mixed overstory dominated by Java Plum (*Syzygium cumini*) and Hau (*Hibiscus tiliaceus*). The ridge is steeply sloped (25-40%), 160 meters above sea level, and has an annual rainfall of 1370 millimeters (Giambelluca et al., 2012). The ridge is the first phase of Kāko‘o ‘Ōiwi’s strategic plan to restore 88 hectares to native forest and agroforest.

**Co-design, trait-based approach Part I: Project visioning**

Members of the University of Hawai‘i (UH) team and Kāko‘o ‘Ōiwi staff previously collaborated on an assessment of lo‘i kalo restoration outcomes (Bremer et al., 2018), which accelerated the design process described here. Four Kāko‘o ‘Ōiwi and He‘eia NERR staff and four UH researchers met in September 2018 to understand a) how the restoration will contribute to the long-term vision of He‘eia, b) what the ecosystem service goals are, and c) what scenarios to test (Fig. 2.2). For each meeting objective, participants free listed responses to a prompt, combined their responses, and grouped responses into categories.
Figure 2.2. An integrated research design process for species selection that embeds a functional trait approach (Ostertag et al., 2015) within a co-production framework. In the case study described in this article, practitioners and researchers collaborated on Steps 1, 3, and 5; researchers led Steps 2 and 4.

Through this process, Kākoʻo ʻOiwi and NERR staff envisioned the relationship of the ridge to the other farm zones in space and time. Rising from a 43 hectare wetland, the ridge is the
highest point in Kāko‘o ʻŌiwi’s core management zone. This setting combined with the traditional name, Pu‘ulani (meaning spiritual ridge), contributed to the vision expressed in the meeting that this is a “place where kanaka [Indigenous Hawaiians] can identify and align their piko [energy centers]” and engage in traditional and contemporary practices. Pu‘ulani is not only envisioned as a place for kanaka to connect with their ancestors and descendants, but also as the piko i of the farm itself – an elevated zone where individuals connect with their ʻaumakua (ancestors) and are nourished spiritually. In this piko framework for the farm, Pu‘ulani is related and aligned with the surrounding wetland, piko o, where kalo feeds in the present. Lessons learned from Pu‘ulani will inform the restoration of other uplands in He‘eia and beyond.

The project goals stem from this vision of Pu‘ulani. Two interrelated goals are to strengthen community connections to the forest and each other and increase community access to native plants for hula, medicine, and other cultural uses. Kāko‘o ʻŌiwi also emphasized improving native species diversity and ecosystem services including sediment retention, water quality regulation, and carbon sequestration. Sediment retention is particularly important. First, because of Kāko‘o ʻŌiwi’s coastal location and responsibility within the ahupua‘a system to improve He‘eia stream water quality for the fishpond below. Second, retaining soil on the landscape can improve soil health, which underpins plant growth, survival, and provisioning services. A final goal is to keep input costs low so that Pu‘ulani contributes to Kāko‘o ʻŌiwi’s financial sustainability.

The last of objective of the visioning meeting was to determine two testable scenarios for operationalizing the vision and goals. Based on the interests in transitioning the non-native forest to a hybrid system and retaining sediment, we designed an experiment to test the effects of two restoration scenarios: early successional facilitation and erosion control. Species selected for both scenarios would also need to meet the socio-cultural and economic goals.

**Co-design, trait-based approach Part II: Trait data collection and analysis**

After setting the vision, goals, and scenarios, we conducted a functional trait analysis following the steps described in Ostertag et al. (2015) (Fig. 2.2). For each scenario, we reviewed academic literature to identify correlated functional traits. Then, we created a list of 106 candidate species compiled from the project visioning meeting and documentation of current and
past Pacific Island agroforestry systems (Elevitch, 2015; Kurashima et al., 2017; Ticktin et al., 2018; Winter et al., 2018).

We compiled trait data from existing databases (Kattge et al., 2011), local practitioner knowledge, and ‘ōlelo no‘eau [Hawaiian proverbs] into a species by trait matrix. When species means were unavailable, we used qualitative data to categorize or rank species (see categories in Table 2.1). For example, we categorized ‘a‘ali‘i’s root type from evidence in the ‘ōlelo no‘eau, “He ‘a‘ali‘i ku makani mai au; ‘a‘ohe makani nana e kula‘i” [I am a wind-resisting ‘a‘ali‘i; no gale can push me over] (Pukui and Dietrich 1983). For each scenario we included four traits that had data available for at least 75% of the candidate species: leaf area, root system typology, clonality, and roundness for erosion control and leaf area, stem specific density, seed mass, and nitrogen fixation for early successional facilitation (Table 2.1).

**Table 2.1.** Functional traits predicted to influence the rates of ecological processes associated with each restoration scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Trait</th>
<th>Significance</th>
<th>Trait Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Successional</strong></td>
<td><strong>Facilitation</strong></td>
<td><strong>Leaf area (cm²)</strong> Positive correlate of a plant's potential relative growth rate</td>
<td><strong>0.11 – 12,240</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Stem specific density (g/cm³)</strong></td>
<td>Positive correlate of a plant's potential relative growth rate</td>
<td><strong>0.1 – 0.95</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Seed mass (g/1000)</strong></td>
<td>Low seed mass indicates resource allocation and dispersal strategy favored in recently disturbed areas</td>
<td><strong>0 – 576,800</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Nitrogen fixation</strong></td>
<td>Ability to fix N is important in N limited environments</td>
<td><strong>N fixing, not N fixing</strong></td>
</tr>
<tr>
<td><strong>Erosion Control</strong></td>
<td><strong>Leaf area (cm²)</strong></td>
<td>Large leaves have a large interception area, which can protect soil from rainfall and increase sediment trapping ability (Burylo et al., 2012, 2014; Kervroëdan et al., 2018)</td>
<td><strong>0.11 – 12,240</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Root type</strong></td>
<td>Small flexible roots hold soil particles together, increase soil shear strength (Stokes et al. 2009), and have stronger tensile strength than thick roots (Burylo et al., 2012, 2014)</td>
<td>fibrous, lateral, plate, tap</td>
</tr>
<tr>
<td></td>
<td><strong>Clonality</strong></td>
<td>Rhizomes or stolons can form mats that hold surface soil</td>
<td>clonal, nonclonal</td>
</tr>
<tr>
<td></td>
<td><strong>Roundness</strong></td>
<td>Plants wider than tall associate with more trapped sediment (Burylo et al., 2012)</td>
<td>1 – 5 ranking</td>
</tr>
</tbody>
</table>
Finally, we used multivariate analysis to explore the functional traits of species. This technique allowed us to visualize each species’ functional profile in relation to other species’ functional profiles and predict which species might have the greatest influence on the desired ecosystem processes. Using Principal Component Analysis (PCA), we projected each species to a specific x,y location in ‘trait space’ for each of the two scenarios described above. We then made a list of plants most likely to impact the desired ecosystem processes for each scenario.

Co-design, trait-based approach Part III: Participatory species selection

We met at Kākoʻo ‘Ōiwi to further refine the species lists by socio-cultural and economic goals. This was an iterative process to ensure selection of under-, mid-, and overstory plants for each ecological scenario that best fit the vision for Puʻulani. We selected eight species unique to each scenario and four species to include in both scenarios (Table 2.2). All species are either native to Hawaiʻi or Polynesian introductions except one (*Symphytum officinale*). The native species are from different Hawaiʻi ecosystems.

Table 2.2. Native (*), Polynesian introduced (+), and non-native species selected through a co-design, functional trait approach for two restoration scenarios.

<table>
<thead>
<tr>
<th>Story</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-</td>
<td>‘Ohi’a lehua mamo</td>
<td><em>Metrosideros polymorpha</em></td>
<td>lei, hula, ceremony</td>
<td>‘Ohi’a lehua ahihi</td>
<td><em>Metrosideros tremuloides</em></td>
<td>lei, hula, ceremony</td>
<td>Koa</td>
<td><em>Acacia koa</em></td>
<td>lei, wood products</td>
</tr>
<tr>
<td>Mid-</td>
<td>Iholena</td>
<td><em>Musa spp.</em></td>
<td>Food</td>
<td>Maile</td>
<td><em>Alyxia stellata</em></td>
<td>lei</td>
<td>Aweoweo</td>
<td><em>Chenopodium oahuense</em></td>
<td>ceremony</td>
</tr>
<tr>
<td>A’ali’i</td>
<td><em>Dodonaea viscosa</em></td>
<td>lei, hula, medicine</td>
<td><em>Awa</em></td>
<td><em>Piper methisticum</em>+</td>
<td>drink, ceremony, medicine</td>
<td>Puuloao</td>
<td><em>Hibiscus arnottianus</em></td>
<td>lei</td>
<td></td>
</tr>
<tr>
<td>Pohinahina</td>
<td><em>Vitex rotundifolia</em></td>
<td>lei, hula, medicine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Māmaki</td>
<td><em>Pipturus albidus</em></td>
<td>tea, medicine</td>
</tr>
<tr>
<td>Under-</td>
<td>Kupukupu</td>
<td><em>Nephrolepis cordifolia</em></td>
<td>lei, hula</td>
<td>Palapalai</td>
<td><em>Microlepia strigosa</em></td>
<td>lei, hula</td>
<td>Nanea</td>
<td><em>Vigna marina</em></td>
<td>lei</td>
</tr>
<tr>
<td>Comfrey</td>
<td><em>Symphytum officinale</em></td>
<td>medicine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ilie’e</td>
<td><em>Plumbago zeylanica</em></td>
<td>n/a</td>
</tr>
<tr>
<td>‘Aki’aki</td>
<td><em>Sporobolus virginicus</em></td>
<td>n/a</td>
<td></td>
<td>Pu’uka’a</td>
<td><em>Cyperus trachysanthos</em></td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ahu’awa</td>
<td><em>Cyperus javanicus</em></td>
<td>‘awa preparation</td>
<td></td>
<td></td>
<td>Uhaloa</td>
<td>Waltheria indica*</td>
<td>medicine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
BENEFITS, CHALLENGES, AND APPLICATIONS OF AN INTEGRATED APPROACH

Embedding a functional trait approach to species selection within a co-production framework has several advantages over applying either approach alone (Table 2.3). A significant challenge of a functional trait approach is insufficient trait data. For example, trait coverage in TRY, the largest global database, is biased towards more abundant species, highest for northern temperate trees and globally distributed pasture species, and low for crop species (Kattge et al., 2020). Integrating co-production and functional trait approaches, however, moves beyond data limitations by creating a structure for integrating indigenous and local knowledge into the design process. Co-production by definition integrates indigenous and local knowledge and Western science by engaging stakeholders in the research process from the start (Norström et al., 2020).

In a functional trait approach to design (Ostertag et al., 2015), any characteristic of a species can be analyzed as a trait and trait values can be numeric or categorical. Thus, a co-design, functional trait approach is flexible to including traits used by local and indigenous communities in management, which are often different from traits used by Western ecologists, such as leaf pliability (Hummel & Lake, 2015), yield, and price as indicators of provisioning services.

Table 2.3. Challenges of each research approach and the corresponding benefits to integrating the two approaches.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Challenge of the approach alone</th>
<th>Benefit to integrating the approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional trait-based design</td>
<td>The limited availability of trait data can impede the applicability of this approach (Laughlin, 2014; Ostertag et al., 2015)</td>
<td>Structure for including indigenous and local knowledge increases data availability</td>
</tr>
<tr>
<td></td>
<td>Research interventions designed with this approach do not necessarily take into account stakeholder interests or needs</td>
<td>Locally important species and ecosystem services are included in research</td>
</tr>
<tr>
<td>Co-production of knowledge</td>
<td>Often produces site specific findings that are difficult to apply to other sites (Lemos et al., 2018)</td>
<td>A trait-based approach is simple design framework that can be applied elsewhere even if actual species selected in co-production are site specific. Research outcomes have current and future utility.</td>
</tr>
<tr>
<td></td>
<td>Constraints of research design can conflict with stakeholder goals</td>
<td>Still a challenge of integrated approach; however, the focus of a trait-based approach on characteristics rather than species creates more flexibility</td>
</tr>
<tr>
<td></td>
<td>Unequal power dynamics can undermine the process and outcomes (Turnhout et al., 2020), potentially yielding design outputs that are not robust for either group’s goals</td>
<td>Still a challenge of an integrated approach</td>
</tr>
</tbody>
</table>
Implementing a functional trait approach alone for research design may not take into account stakeholder interests, yet, when combined with co-production, may lead to locally relevant species and ecosystem services in research. In Heʻeia, the two selected species assemblages, primarily native, yet not from a single reference ecosystem, are unlike models of agroforestry promoted in Hawaiʻi (e.g., NRCS, 2013) and elsewhere. However, these assemblages include plants that produce non-timber forest products in high demand by local communities (Kamelamela, 2019). Stakeholder involvement in functional design of research interventions can produce designs that more closely reflect the species and ecosystem service goals important to communities, the absence of which may limit agroforestry establishment globally (Dumont et al., 2019).

Similarly, an integrated approach can have both current and future utility for restoration science and practice. Co-production alone can produce locally relevant research; however, it often produces site-specific findings that can be difficult to generalize to other contexts (Lemos et al., 2018). Conversely, as functional restoration is founded in generalizable and predictive knowledge (e.g., nutrient uptake strategy diversity increases nutrient availability) rather than context specific knowledge based on species identities (e.g., intercropping taro and breadfruit increases nutrient cycling), it can transform the applicability of research findings. Restoration interventions co-designed with stakeholders using a trait-based approach will have direct value locally and will be structured to document outcomes in a way that is reproducible and applicable to other practitioners – a restoration priority (Cooke et al., 2019). Yet, an integrated approach still has challenges of other co-production applications. For example, the constraints of research design can conflict with stakeholder goals, and failure to address unequal power dynamics among researchers and stakeholders can undermine the process (Turnhout et al., 2020), potentially yielding design outputs not robust for either group’s goals.

In contexts where introduced species and climate change have rapidly and drastically changed plant communities, restoring to a native reference ecosystem may not be ecologically, economically, or logistically feasible, and thus restoring ecosystem services or functions may be preferable. In these cases, co-designing research interventions using a trait-based approach can improve inclusion of indigenous and local knowledge and locally-relevant species while still producing generalizable results. Taking an inclusive, scalable approach to designing interventions at the intersection of forest restoration and diversified agriculture can accelerate the
mutual goal of restoring biodiversity and ecosystem services, an important step in ensuring the Decade on Restoration translates to meaningful conservation gains.

ACKNOWLEDGMENTS

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CHAPTER 3. NON-NATIVE FORESTS HOLD HIGH POTENTIAL FOR RESTORATION THROUGH AGROFORESTRY IN A PACIFIC ISLAND ECOSYSTEM

To be submitted as:

ABSTRACT
The expansion and intensification of agriculture is a significant driver of deforestation. Yet, when land is left fallow for long periods of time, spontaneous forest regeneration can occur. In places where non-native species dominate successional pathways, such as in the Hawaiian Islands, unmanaged agricultural lands often transition to non-native dominant forests. Although non-native forests that have naturally regenerated on fallow agricultural lands can still provide a range of ecological benefits, their agricultural production and cultural benefits are often low. Restorative practices, like agroforestry, that integrate native and non-native, culturally important plants have the potential to increase biodiversity and ecosystem services of fallow agricultural lands. However, understanding what the restoration potential is of different agroforestry pathways remains a question. We collaborated with a community-based non-profit organization working to restore agroecological productivity to former agricultural lands while perpetuating Native Hawaiian cultural practices to explore the potential of restoring biodiversity and ecosystem services to fallow agricultural land using agroforestry. We asked, 1) does the composition of agroforestry species planted (i.e., treatment) affect restoration success, and if so, do other factors mediate the effect of treatment, and 2) how do ecological conditions two years post-restoration compare to conditions pre-restoration? We set up ten 12 × 15 m restoration plots and one reference plot on forested former pasture land. Then, we used a functional trait-based approach to select two different agroforestry species mixes that both had high cultural value and each were selected for traits to address a different primary ecological goal: erosion control and early successional facilitation. We monitored the plant communities before restoration and at 6 months, 1 year, and 1.5 years post-planting. Then, we used multi-variate analysis and structural equation modeling (SEM) to analyze the differences between treatments over time. We found
that restoration success did not vary significantly between treatments in the first two years of restoration. Results of the SEM indicate that variability in understory cover of agroforestry species was primarily an issue of management factors not tested in the model. This study provides a first step in documenting what non-native forest to agroforest transitions can look like. Taken together, our findings suggest that non-native forests on fallow agricultural land have a high potential for restoration through agroforestry in Pacific Island ecosystems.
INTRODUCTION

The expansion and intensification of agriculture is considered one of the most significant drivers of deforestation (IPBES, 2018). However, political-economic factors, such as increased labor costs, decreased crop prices, and changes in land use policy, can cause farmers, ranchers, and land owners to leave land fallow (Barbier et al., 2010; Rudel et al., 2010). When left unmanaged long enough, spontaneous forest succession can occur (Mather, 1992; Meyfroidt and Lambin, 2011; Rudel et al., 2005; Wilson et al., 2017). Therefore, although forest area continues to decline globally, in many regions new forest cover is increasing, for example in Western Europe and the United States (Rudel et al., 2005) and more recently in many tropical countries (Aide et al., 2013; Wilson et al., 2017). In cases where new forest cover is the result of natural forest succession, rather than intentional restoration or tree planting, new forests can remain ecologically distinct from the forests previously cleared for agriculture since the general structure of forests often recovers much faster than species composition (Chazdon et al., 2016; Dent and Wright, 2009; Meyfroidt and Lambin, 2011). In places where non-native species dominate successional pathways, such as the Pacific Islands, species composition recovery is often arrested (Guariguata and Ostertag, 2001; Hughes et al., 2014). While non-native dominated forests regenerated on agricultural fallows can still provide some supporting and regulating like erosion control (Ewel and Putz, 2004) and carbon storage (Melone et al., 2021), they often provide fewer products for harvest and cultural use, particularly when compared to native dominated forests and agricultural systems. With climate change expected to decrease agricultural production and increase food insecurity and biodiversity loss (IPCC, 2019), managing agricultural fallows for both ecological and social benefits is a high priority.

Agroforestry is one potential tool for restoring biodiversity and ecosystem function in a way that also provides social benefits. The term agroforestry encompasses a spectrum of practices that integrate trees and shrubs with other tended and harvested plants or animals. Agroforestry systems are linked human-natural systems (Liu et al., 2007) that are often based in Indigenous and local knowledge (Berkes, 2008). Although agroforestry transitions can include manipulating the understory of native forests (Ollinaho and Kröger, 2021), on former agricultural lands, agroforestry practices can be a form of hybrid restoration (Burnett et al., 2019; Hobbs et al., 2014). In these cases, integrating agricultural production into forest restoration can help offset planting and maintenance costs with crop and nontimber forest product sales (Vieira et al.,
2009) thereby improving livelihoods (Miccolis et al., 2019). A major gap in restoring a broader suite of ecosystem services to non-native species dominant fallows, however, is understanding what the potential is of non-native forests for restoration through agroforestry and what types of agroforestry practices make for viable transition pathways.

Hawai’i’s land use history and current social-ecological context provide an important case study for developing a deeper understanding of the restoration potential of non-native dominant fallow agricultural lands using agroforestry. Non-native dominant forests make up 40% of the total forest cover in Hawai‘i (Selmants et al., 2014). These forests arise from two primary pathways: 1) succession on former commercial agricultural lands, and 2) invasion into formally native-dominated ecosystems and Indigenous agroecosystems, including areas managed with Indigenous agroforestry prior to colonization (Kurashima et al., 2019; Lincoln et al., 2018; Quintus et al., 2019). Non-native forests can decrease erosion, hold water, and provide other ecosystem services (Ewel and Putz, 2004), yet they are often less desirable than native forests as they contain lower native biodiversity and threaten native forests through the dispersal of non-native species (Vorsino et al., 2014). Yet, non-native forests can be costly to restore (Burnett et al., 2019), so conservation organizations have allocated what little funding is available to protecting remaining native forests and restoring native forest at higher elevations, where more native plants still exist (DLNR, 2011; Friday et al., 2015). Even though many non-native forests in Hawai‘i hold less cultural value than native dominant systems (Burnett et al., 2019), they mostly occur in low elevation areas near where people live. This suggests potential for biocultural restoration, or the mutually reinforcing restoration of land and culture (Kimmerer, 2011; Kurashima et al., 2017). Assessing this potential and understanding how different agroforestry practices could affect restoration outcomes in the establishment phase is critical to developing scalable restoration solutions.

We designed a study to investigate the effects of restoration treatment (i.e., agroforestry species mix) on plant outcomes over the first two years of a non-native forest to multi-story agroforest transition on fallow pasture. We asked, 1) do initial measures of restoration success (i.e., understory composition, understory cover, and mid- and over-story survival) vary between treatments over the first two years, and if so, are these treatment effects mediated by other drivers, and 2) how do ecological conditions in the first two years compare to pre-restoration? We selected species for restoration treatments using a co-produced, functional trait approach.
(Hastings et al., 2020), meaning we worked with community partners from the very beginning to design the experimental restoration and select species based on both cultural value and their predicted effect on ecosystem function. This approach allowed us to include culturally important native species that are often left out of agroforestry research and link results to plant functional groups rather than species alone so that results would be both locally relevant and applicable to other sites (Hastings et al., 2020). We hypothesized that treatment, canopy cover, and understory weed cover would have direct effects on agroforest outplant survival and understory cover of agroforestry species, and that the effects of treatment and canopy cover would also be mediated by understory weed cover. We used a structural equation modeling (SEM) approach to analyze the factors affecting initial restoration success because it allowed us to analyze the factors as a system, which is critical when predictor variables, such as ours, are not independent (Grace, 2006).

METHODS

Study Site

This study took place in Heʻeia on the windward side of the island of Oʻahu, Hawaiʻi. Heʻeia is an ahupuaʻa, a Native Hawaiian social-ecological land division (Winter et al., 2018), where several community-based non-profit organizations collaborate to restore Kānaka ʻŌiwi land management practices including loʻi kalo (wetland taro, *Colocasia esculenta*), loko iʻa (fish pond aquaculture), and agroforestry (Fig. 3.1) (Bremer et al., 2018; Hastings et al., 2020; Winter et al., 2020). Part of the ahupuaʻa was designated as a National Estuarine Research Reserve (NERR) in 2017. The Heʻeia NERR is the first to intentionally focus on the restoration of social-ecological systems, and one of their primary goals is to understand the potential of biocultural restoration to enhance multiple ecosystem services (Winter et al., 2020).

The restoration took place on a ridge called Puʻulani (heavenly ridge) within the Heʻeia NERR stewarded by Kākoʻo ʻŌiwi, a community-based non-profit whose mission is to perpetuate the cultural and spiritual practices of Native Hawaiians. Puʻulani is part of a 164 ha parcel that Kākoʻo ʻŌiwi leases from the Hawaiʻi Community Development Authority. We collaboratively selected Puʻulani as the study site because it was adjacent to existing management zones, and aligned with the next phase of the organization’s restoration plan. Within the restoration plan, Puʻulani is designated as a pilot area for the restoration of an
additional 88 hectares of upland non-native dominant forest to native forest and agroforest. Pu‘ulani is approximately 4,000 m², sloped (25–30%), located 160 m above-sea-level, and has a mean annual rainfall of 1370 mm (Giambelluca et al., 2012). The soils are classified as Ultisols (Loleka‘a silty clay) and Inceptisols (Hanalei silty clay) according to USDA Natural Resource Conservation Service data (Deenik et al., 2014); however, to our knowledge, no one has done an onsite soil classification.

**Figure 3.1.** The study area, Pu‘ulani, is stewarded by the non-profit organization Kākoʻo ʻŌiwi and located within the ahupua‘a (Native Hawaiian land division) of He‘eia in Koʻolaupoko, O‘ahu. The solid orange line represents the ahupua‘a boundary in the Hawaiʻi Statewide GIS Program Ahupua‘a GIS Layer; however, historical ahupua‘a boundaries would have included the He‘eia fishery, which is represented approximately by 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). Figure is reproduced from Melone et al. (2021).

Pu‘ulani has a land use history similar to other coastal, low elevation sloped lands in Hawai‘i. Prior to European contact (1778) and until the mid-1800s, Pu‘ulani was stewarded by Kānaka ʻŌiwi (Native Hawaiians) likely as a form of Indigenous agroforestry, a mixed native
and Polynesian introduced forest stewarded for food, medicine, ceremony, and other uses (Kurashima and Kirch, 2011; Lincoln, 2020). In 1848, the Māhele (division of land), led to the privatization of land and accumulation of land by non-Hawaiians (Kameʻeleihiwa, 1992). Sugar and pineapple plantations came to dominate the agricultural and political landscape. Like other sloped lands, Puʻulani escaped intensive cultivation of row crops during the plantation era. However, Kānaka ʻŌiwi land dispossession following the Māhele led to the transition to pasture and cattle grazing on the sloped areas of Heʻeia, including Puʻulani (Peloso and Peloso, 2010). Puʻulani experienced an estimated 30-60 years of cattle grazing before becoming fallow for at least the past 70 years (Peloso and Peloso, 2010). Without active management along Puʻulani’s slopes, however, ecological succession proceeded leading to dominance of non-native forest cover (Appendix 3.1).

**Experimental Design**

Prior to starting any clearing or restoration, we set up eleven 12 × 15 m plots across the eastern facing slope of Puʻulani, including one control plot and five replicate plots for each of the two treatments. Plot lengths accounted for slope. We spaced each plot five meters apart. We separated the plots into two blocks to account for environmental variation, and we randomly assigned plots within each block to a treatment (i.e., agroforestry species mix). We drew a 2 × 2 m grid representing 12 × 14 m of each plot and then randomly selected six squares per plot to become subplots. At the site, we measured and marked the location of each 2 × 2 m subplot for a total of 30 subplots per treatment.

Treatments consisted of two communities of agroforestry species, each selected for the same social benefits and a different primary ecological benefit. To select species, we followed a design process that embedded functional-trait based design for restoration (Ostertag et al., 2015) into a co-production framework (Norström et al., 2020). The process included five steps: 1) formulate vision goals, scenarios, and species pool, 2) select traits for goals, 3) collect trait data, 4) analyze trait data and filter species predicted to enhance goals, and 5) select species from trait-filtered lists based on additional goals and constraints (Hastings et al., 2020). One restoration treatment focused on early successional facilitation and included species based on the following traits: leaf area (small), stem specific density (low), seed mass (small), and nitrogen-fixation ability (Hastings et al., 2020). The other restoration treatment included plants with large leaf
area, fibrous roots, clonal growth, and round structure with the goal of improving erosion control (Hastings et al., 2020). Each treatment included eight species unique to the treatment and four species shared between the treatments for twelve species total in each treatment (Appendix 3.2).

We conducted baseline monitoring in October 2018 and started the restoration in December 2018. We were unable to measure the pre-restoration plant community in one plot due to the density of hau (*Hibiscus tiliaceus*) branches. We selectively thinned the existing overstory and hand-cleared the understory of the 10 treatment plots in December 2018. We planted 2,740 individuals of twenty species between January and May 2019. Each treatment plot had a density of eight trees, eighty shrubs, and 186 understory outplants per plot. We individually tagged and numbered all outplanted shrubs and trees. All treatment plots received approximately equal level of weeding for the full study period and irrigation up until one year post-planting. Weeding was done by hand by the researchers, non-profit staff, and many different volunteer groups.

**Data collection and analysis**

We measured the initial size of all outplanted shrubs and trees and re-monitored at six months, one year, and 1.5 years post-planting. At each re-monitor, we noted survival and measured the basal diameter and height of all outplanted trees and shrubs. Then, at the subplot level, we visually estimated percent understory cover by species. We also took soil moisture and hemispheric photographs of the canopy in each subplot. After each census of the understory, we removed weeds by hand across all of the treatment plots.

For analyses, we first assessed changes in understory plant species composition over time using nonmetric multidimensional scaling (NMDS) in the Community Ecology Package (vegan; version 2.5-7) (Oksanen et al., 2020) in R (version 3.6.2) (R Core Team, 2020). We excluded species abundance from a subplot’s composition data if they were recorded present in the subplot, but had less than 5% cover to prevent overinflating the role these species played in the plant community and to improve the stress of the NMDS.

Then, we tested the effects of treatment and other drivers on understory cover of agroforestry species. We analyze three factors in addition to treatment: percent canopy cover, percent understory cover of weeds, and dominant weed species. We used the program Gap Light Analyzer to determine the percent canopy cover from hemispheric photos (Frazer et al., 1999). Then, we grouped species recorded in the understory into agroforest species (planned) and weed
species (unplanned) to determine the percent cover of weeds and agroforest species. Next, we developed the variable dominant weed species by grouping weed species into three functional types – graminoid, climbing, and mat-forming – and then classifying the subplots by dominant weed type when they had at least 40% cover of one type. If a subplot had less than 40% cover of any weed type, we classified the subplot as mixed. We ranked the dominant weed types from least predicted to affect understory cover of agroforestry species to most likely based on a gradient of density of root and surface cover: 1) mixed (no dominant type), 2) graminoid, 3) climbing, and 4) mat-forming. We did not include soil moisture as a predictor because soil moisture data did not have sufficient variability across subplots in two of the three censuses due to soil saturation.

We first used general linear mixed models (Zuur et al., 2009) to regress predictors against understory cover of agroforestry species per subplot. We used the package Generalized Linear Mixed Models using Template Model Builder (glmmTMB; version 1.1.2.3) (Brooks et al., 2017) and a negative binomial response distribution. Models included the random effect of subplot nested within plot to account for potential spatial autocorrelation. We examined model residuals for homogeneity of variance and variables for multicollinearity. We used single-variable regressions as opposed to multiple because predictors were not independent. Because there was a drought in the second half of the study, we examined understory cover for two time periods: 1) six months to one year post-planting (under average rainfall conditions) and 2) one year to 1.5 years post-planting (under drought conditions). We excluded the time period 0 – 6 months because survival during this time was likely driven by transplant shock, the initial size of outplants, and other factors specific to outplanting conditions.

We used structural equation modeling (SEM) (Grace, 2006) to identify how predictors correlate directly or indirectly with understory agroforestry species cover. We did not use dominant weed as a predictor in the SEM because our sample size was not large enough to support more than three predictors. To account for spatial autocorrelation, we used a nested structure of subplots within plots. We started with a model of hypothesized links (Fig. 3.2a) and thereafter used modification indices to identify missing paths (Grace, 2006). We added missing paths that were grounded in theory or existing knowledge (Grace, 2006) and then sequentially eliminated nonsignificant correlations. We determined the best fit model by comparing all
models with Akaike’s information criterion. We used the lavaan package (Rosseel, 2012) to conduct the SEM.

We did not build an SEM for the mid- and over-story outplant survival data. Plot level predictor variables did not have sufficient variability to analyze the hypothesized relationships using SEM. Instead, we used a binomial regression with species and plot as random factors to compare the mean survival rates across treatments. We also calculated survival rates for each species. We carried out all statistical analyses in R (version 3.6.2) (R Core Team, 2020).

Figure 3.2. Hypothesized (a) and best fit (b, c) structural equation models (SEM) of drivers of agroforestry understory cover at one year post-planting (b) and 1.5 years post-planting (c). Best fit models (b, c) present the standardized path coefficients, which represent the predicted change in standard deviation units. A dotted line between variables represents an insignificant link that remained in the best fit model. As a predictor, understory weed cover is the percent cover of weeds six months prior to the measurement of the response variable. Although the hypothesized model includes outplant survival as a response variable, we were unable to analyze the survival data using SEM because of low variability within the predictors at the plot level.
RESULTS

Effect of treatment on restoration success

First, we found no difference in a suite of plant community metrics across treatments in the first two years of restoration (Table 3.1). We selectively thinned existing trees as a part of the restoration, leaving roughly the same tree density at the time of outplanting. However, after one year post-planting, erosion control treatment plots had higher tree density than early succession plots because mai’a iholena lele (Musa sp.) quickly grew to a size that provides a similar shade function as trees. Canopy cover was similar across treatments, despite the new contribution to shade by mai’a. Both treatments had high variability in percent understory cover of weeds. The two treatments had the same mean species richness of native and/or culturally important species at one year post-planting, which included some mid-story outplants that were providing understory cover at that growth stage. Species richness of weeds was similar in both treatments.

Table 3.1. Summary of plant community characteristics before restoration (non-native forest before clearing), 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. During the first year post-planting, the site experienced normal rainfall levels, however, for the following six months the site experienced drought conditions. Values presented are plot means.

<table>
<thead>
<tr>
<th></th>
<th>Pre-restoration (October 2018)</th>
<th>1 yr post-planting (March 2020)</th>
<th>1.5 yrs post-planting (October 2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>S</td>
<td>E</td>
</tr>
<tr>
<td>Tree density (no. trees ≥ 5 cm DBH)</td>
<td>5.4 ± 2.6</td>
<td>4.8 ± 2.6**</td>
<td>10.8 ± 0.8</td>
</tr>
<tr>
<td>Canopy cover (%)</td>
<td>82.4 ± 2.7</td>
<td>84.4 ± 3.7</td>
<td>71.0 ± 6.6</td>
</tr>
<tr>
<td>Understory cover of weed species (%)</td>
<td>87.5 ± 9.4</td>
<td>87.2 ± 6.6**</td>
<td>57.0 ± 30.7</td>
</tr>
<tr>
<td>Species richness of understory native and/or culturally important plants</td>
<td>0</td>
<td>0</td>
<td>4.8 ± 1.1</td>
</tr>
<tr>
<td>Species richness of understory weeds</td>
<td>8.3 ± 2.9</td>
<td>8.4 ± 3.0</td>
<td>10.4 ± 1.8</td>
</tr>
</tbody>
</table>

*This includes mai’a iholena lele (Musa sp.) greater than 2 m height.

**This excludes one outlier: a plot that had 25 trees and 10% understory cover of weed species.
One on one regressions of predictor variables and understory cover of agroforest species showed that understory cover of weed species and dominant weed type at the previous re-monitor were both significantly negatively correlated with understory cover of agroforest species at both one year and 1.5 years post-planting (Fig. 3.3). The negative correlation between understory cover of agroforestry species and dominant weed type at the previous re-monitor means that the understory cover of agroforestry species decreases across subplots that have dominance of mixed (type = 1), graminoid (type 2), climbing (type = 3), and mat-forming (type = 4) weeds in the previous re-monitor.

Figure 3.3. Regressions of predictors of understory cover of agroforestry species at one year post-planting (a) and 1.5 years post-planting (b) at a restoration site in Hawai‘i. As predictors, understory cover of weed species and dominant weed type are from the census previous to the census where the dependent variable, understory cover of agroforestry species, was measured.
Plots with regression lines represent significant correlations ($p < 0.01$). Plots without lines do not have a significant relationship. All models include subplot nested within plot as a random term.

The structural equation model (SEM) for understory cover of agroforestry species also showed no significant effect of treatment. The best fit structural equation model for the time periods from six months to one year post-planting ($\chi^2 = 0.860$) and from one year to 1.5 years post-planting ($\chi^2 = 0.957$) explained 27.3% and 29.2% of the data respectively (Fig. 3.2b and c). Path coefficients are the expected change in one variable resulting from a change in another while holding all other variables constant (Appendix 3.3). Figure 3.1 presents the standardized path coefficients, which represent the predicted change in standard deviation units, and allow for comparisons between variables. For both time periods, understory cover of weed species at one re-monitor was negatively correlated with understory cover of agroforestry species at the following re-monitor. Therefore, subplots with higher understory cover of weeds at six months post-planting had lower understory cover of agroforest species at one year, and subplots with higher understory cover of weeds at one year post-planting had lower understory cover of agroforest species at 1.5 years. In the first year post-planting, canopy cover had an indirect negative effect on understory cover of agroforestry species. Although this link remained in the best fit model, it was insignificant ($p = 0.168$). In the second year post-planting, treatment was negatively correlated with canopy cover, meaning that subplots with the treatment erosion control had higher canopy cover. However, this link was insignificant ($p = 0.247$) even though it remained in the best fit model.

Survival of mid- and over-story outplants did not vary between treatments (Fig. 3.4). There was no significant effect of treatment on survival ($p=0.50$). Survival rates, however, did vary by species (Fig. 3.4). With the exception of ʻōhiʻa lehua mamo (*Metrosideros polymorpha*) and māmaki (*Pipturus albidus*), species selected for their functional traits associated with ecological goals had higher survival rates than the three species used in both treatments that were not selected based on their functional traits.
Figure 3.4. Survival rates by species (dashed lines) and the mean survival rate for each treatment (solid lines) at a restoration site in Hawai‘i. For Latin names of species, see Appendix 3.2. During the first year post-planting, the site experienced normal rainfall levels; however, from 1 year to 1.5 years post-planting, the site experienced drought conditions.

Comparison of restoration treatments to the baseline non-native forest

Prior to restoration, Pu‘ulani had 100% non-native tree cover, predominately composed of Java plum (*Syzygium cumini*), fiddlewood (*Citharexylum spinosum*), and octopus tree (*Schefflera actinophylla*) (Fig. 3.5a and b). The primary composition of the forest understory was bare-ground (leaf litter), basket grass (*Oplismenus hirtellus*), wedelia (*Sphagneticola trilobata*), and maile pilau (*Paederia foetida*) (Appendix 1). Tree density was 5.4 ± 2.6 trees per plot in the
erosion control plots and 4.8 ± 2.6 in the early succession plots (Table 3.1). The mean canopy cover was over 80% across all plots. Understory weed cover was also over 80% on average across all plots. The list of species present in the baseline forest, including mean cover for understory species and density for trees, is in Appendix 3.1.

![Figure 3.5. Photographs of Pu‘ulani in He‘eia, O‘ahu before restoration in October 2018 (a, b) and one year post-planting (c, d) in March 2020. Agroforestry treatments included one species mix designed with the primary ecological goal of early successional facilitation (c) and one with the goal of erosion control (d). Both treatments were selected to provide cultural value.](image)

The structure and composition of the plant community shifted from the baseline forest in both treatments (Fig. 3.5c and d). Selectively thinning the canopy, reduced the canopy cover from pre-restoration levels in both treatments (Table 3.1). Understory composition also shifted slightly between pre-restoration (October 2018) and two years later (October 2020) (Fig. 3.6). The shift in species composition post-restoration reflects the addition of outplanted species as
well as higher abundance of some weed species, such as wedelia (*Sphagneticola trilobata*) and hilo grass (*Paspalum conjugatum*).  

**Figure 3.6.** Non-metric multidimensional scaling (NMDS) of understory plant composition before and after restoration using agroforestry at a site in Hawai‘i. Colored points represent subplots. Species Latin names are given in Appendix 3.1 (weeds) and Appendix 3.2 (outplants).

**DISCUSSION**

Agroforestry presents a possible restorative pathway for non-native forests regenerated on fallow agricultural land, but a greater understanding of the potential of non-native forests to be restored through agroforestry and the types of agroforestry practices that are viable is needed. We investigated the effects of treatment (i.e., agroforestry species mix) on metrics of restoration success and the change in plant community structure and composition between pre-restoration
and two years post-restoration. We found no difference between the two agroforestry treatments, however there was a shift in restoration outcomes from pre-restoration. Our results suggest that non-native forests in particular have a high potential for restoration via agroforestry.

First, our results show that two agroforestry treatments had similar restoration outcomes in the short term, providing evidence that in the establishment phase, social-cultural benefits can drive agroforestry species mixes. In terms of the understory, treatment did not affect community composition or cover of agroforestry species. An important caveat, though, is that the understory cover variation we captured was limited, particularly the dataset contained few subplots with agroforestry species cover greater than 30%. Thus, our findings suggest that treatment is not a significant driver of understory cover of agroforestry species when cover is less than 30%. However, treatment could be a significant driver of cover in plots with greater than 30% cover of agroforestry species, but we did not have enough data in that range to capture that effect. The two restoration treatments appear to have the potential to produce high understory cover, but from our findings we are unable to say under what conditions.

Our results further highlight the importance of establishing high understory cover of agroforestry species from the start. The best fit structural equation models for both time periods show the significant relationship between understory weed cover at the previous census and agroforestry cover. Even though we removed weeds between monitoring, the understory outplants did not grow fast enough to keep up with weeds. This indicates that regardless of what species are planted, a management priority should be to achieve high plant cover to keep out weeds. One way to accomplish this is to include more plants with functional traits similar to weed species; more aggressive (but not invasive) nonnatives or cover crops to help establish system, then transition in native understory species. More research is needed, especially in measuring the functional traits of locally important species that are or could be used in agroforestry systems, to assist with the scaling of agroforestry pathways. In particular, studies assessing plant and soil dynamics as mediated by plant root traits is an important research need.

Additionally, we found no difference in survival of mid- and over-story outplants between treatments; however, there was high variability within each treatment. Most mortality occurred in the first year of establishment when factors related to outplant size and environmental suitability are common drivers (Fig. 3.4). These transplant related factors likely affected five species: two in the erosion control treatment, one in the early succession treatment, and two in common
between the treatments. Māmaki (*Pipturus albidus*), and to a lesser extent ‘ohia lehua ahihi (*Metrosideros tremuloides*) and ‘ohia lehua mamo (*Metrosideros polymorpha*), are known to be difficult to transplant (Lilleeng-Rosenberger, 2016). Additionally, outplant size was likely the primary driver of a‘ali‘i (*Dodonea viscosa*) mortality since those individuals were much smaller than individuals of the other species at outplanting. Maile (*Alyxia stellata*), a mid-story native forest plant, would likely have had higher survival if planted into more established systems because of moisture and light requirements (Whitehead, 2015).

Looking past these five species, however, we see that the other six species had moderate to high survival rates, including during the period of drought. All but two of these species were selected for their traits related to early successional facilitation. Although mai‘a iholena lele (*Musa sp.*) and pohinahina (*Vitex rotundifolia*) were selected for their erosion control traits, both species also have traits that make them well adapted to early successional environments, such as fast growth rates and high sun tolerance. This finding could indicate a potential advantage to including at least some species adapted to early successional environments in any agroforestry treatment mix. As a natural drought occurred at the site in the last six months, species with the highest survival rates are not only suited for agroforestry mixes, but are also likely to tolerate future droughts. This is important as drought is predicted to become more common in Hawai‘i with climate change (Heleg and Keener, 2017), necessitating selection of drought resilient species and management practices. Although ‘awa (*Piper methisticum*) had moderate survival rate at one year post-planting, none survived the drought suggesting that ‘awa may need to be planted at sites with higher rainfall levels or in systems with irrigation to be resilient to future drought.

Taken together, our results show that transitions to agroforestry from non-native forest naturally regenerated on agricultural land hold high potential for biocultural restoration in Pacific Island ecosystems. Prior to restoration, the treatment plots contained no native species and only a few non-native species that hold socio-cultural value to the local community. Yet, after two years of restoration activity, and 1.5 years after planting, we observed lower understory cover of weed species and higher species richness of desirable species compared to baseline. While this increase in native biodiversity is important on its own, the ecological shift also has had valuable social and cultural benefits. Prior to restoration, the site was infrequently visited by Kāko‘o‘Oiwi staff and community members; however, just two years after initiating the project, more
than 800 pre-K through college students, halau hula (Native Hawaiian dance school) practitioners, and community members had visited the site to mālama ʻāina (care for the land), learn about the cultural uses of the plants, and harvest plant material for lei (garlands) and food. Further, results of soil health analysis at the site (Appendix 3.4) suggest that non-native forests regenerated from pasture have soil health comparable to other forests in Hawaiʻi and thus could provide a good foundation for restoration. Although the native forest or Indigenous agroforest of Puʻulani was cleared for ranching, and some of the soil health indicators reflect this legacy, the centuries or more of forest cover prior to ranching and last 70 years of non-native forest cover have resulted in soil conditions that are a good foundation for restoration.

Restoring existing non-native forests through agroforestry is often less desirable than transitioning unforested cropland and fallows to agroforestry due to potentially lower net carbon benefits and higher costs to remove undesirable trees. However, our study highlights how a biocultural approach to restoration can help capture value from existing non-native forests. For example, in our case study, selectively removed canopy trees produced organic matter for on-site soil improvement, reducing supplement costs, and remaining trees provided shade to support weed suppression and soil moisture retention. Selectively removed trees can also provide substrate for edible or medicinal mushroom cultivation to offset costs. In cases where non-native forests include economically important tree species, timber sales can help offset restoration costs as well (Brancalion et al., 2020; Pejchar and Press, 2006). Additionally, engaging more community members at Puʻulani through a biocultural approach led to knowledge exchange about management, including the value of non-native plants in other cultures. For example, Java plum (*Syzygium cumini*), the most abundant tree in the baseline forest, is widely used to treat disease in South Asia (Ayyanar and Subash-Babu, 2012), but has not been adopted in lāʻau lapaʻau (Native Hawaiian plant medicine) (Kraus and Noyes, 2001). Learning the cultural uses of non-native plants in their native ecosystems, connecting immigrant communities who have traditional knowledge of the non-native plants with local restoration sites, and developing culturally appropriate value chains for non-native species are all ways to further the potential of non-native forests.

Climate change threatens agricultural production, food security, and biodiversity, necessitating better management of agricultural fallows for both ecological and social benefits. In Pacific Island ecosystems, where non-native species dominate successional pathways, natural
forest succession often leads to non-native forests which can provide fewer social and cultural benefits from native forests or agricultural systems. Our results shows that in these cases, restoration through agroforestry holds high potential to increase social, cultural, and ecological benefits of agricultural falls. Increasing community access to fallow agricultural land, as well as resources for their restoration, should be priorities to fully realize this potential and bolster community resiliency to climate change.

DATA AVAILABILITY STATEMENT

Data and the reproducible R code is available by request from the author. It will also be made available in a public repository.

ACKNOWLEDGEMENTS

We are grateful to the Kākoʻo ʻŌiwi community, without whom this study would not have been possible. We also thank all of the students and community volunteers who have contributed to the stewardship of Puʻulani. Susan Crow, Christine Tallamy Glazer, Angelica Melone, and Elaine Vizka helped with soil sampling and analyzed the soil health indicators presented in Appendix 3.4. We are grateful for contributions to study development made by Clay Trauernicht, Dave Elliot, and Kawika Winter. Becky Ostertag and Rakan Zahawi provide valuable feedback on an earlier draft of this manuscript.
APPENDIX 3.1

Table S1. List of plant species present in the forest prior to restoration (October 2018) at Puʻulani in Heʻeia, Hawaiʻi. Values are plot means and standard deviations.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Family</th>
<th>Species</th>
<th>Understory cover (%)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Understory</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basket grass</td>
<td>Poaceae</td>
<td>Oplismenus hirtellus</td>
<td>36.4 ± 28.8</td>
<td></td>
</tr>
<tr>
<td>Maile pilau</td>
<td>Rubiaceae</td>
<td>Paederia foetida</td>
<td>14.7 ± 10.1</td>
<td></td>
</tr>
<tr>
<td>Wedelia</td>
<td>Asteraceae</td>
<td>Sphagnicola trilobata</td>
<td>10.6 ± 22.9</td>
<td></td>
</tr>
<tr>
<td>Hilo grass</td>
<td>Poaceae</td>
<td>Paspalum conjugatum</td>
<td>5.1 ± 10.1</td>
<td></td>
</tr>
<tr>
<td>Glycine</td>
<td>Fabaceae</td>
<td>Neonotonia wightii</td>
<td>4.7 ± 10.3</td>
<td></td>
</tr>
<tr>
<td>Achyranthes</td>
<td>Amaranthaceae</td>
<td>Achyranthes sp.</td>
<td>2.5 ± 8.2</td>
<td></td>
</tr>
<tr>
<td>Aster</td>
<td>Asteraceae</td>
<td>Aster sp.</td>
<td>1.4 ± 9.7</td>
<td></td>
</tr>
<tr>
<td>Hiptage</td>
<td>Malpighiaceae</td>
<td>Hiptage benghalensis</td>
<td>1.1 ± 10.3</td>
<td></td>
</tr>
<tr>
<td>Honohono</td>
<td>Commelinaceae</td>
<td>Commelina diffusa</td>
<td>0.62 ± 7.9</td>
<td></td>
</tr>
<tr>
<td>Ardisia</td>
<td>Myrsinaceae</td>
<td>Ardisia elliptica</td>
<td>0.42 ± 8.2</td>
<td></td>
</tr>
<tr>
<td>Sida</td>
<td>Malvaceae</td>
<td>Sida rhombifolia</td>
<td>0.25 ± 9.8</td>
<td></td>
</tr>
<tr>
<td>Hilahila (Sensitive plant)</td>
<td>Fabaceae</td>
<td>Mimosa pudica</td>
<td>0.15 ± 8.0</td>
<td></td>
</tr>
<tr>
<td>Adlay (Jobe's tears)</td>
<td>Poaceae</td>
<td>Coix lacryma-jobi</td>
<td>0.10 ± 8.4</td>
<td></td>
</tr>
<tr>
<td>Unknown 1</td>
<td>NA</td>
<td>NA</td>
<td>0.10 ± 8.5</td>
<td></td>
</tr>
<tr>
<td>Vervain (Rattail)</td>
<td>Verbenaceae</td>
<td>Stachytarpheta dichotoma</td>
<td>0.05 ± 8.2</td>
<td></td>
</tr>
<tr>
<td>Unknown 2</td>
<td>NA</td>
<td>NA</td>
<td>0.03 ± 9.7</td>
<td></td>
</tr>
<tr>
<td>Wood sorrel</td>
<td>Oxalidaceae</td>
<td>Oxalis corniculata</td>
<td>0.03 ± 8.3</td>
<td></td>
</tr>
<tr>
<td>Unknown 3</td>
<td>Fabaceae</td>
<td>NA</td>
<td>0.03 ± 8.3</td>
<td></td>
</tr>
<tr>
<td>Kaʻeʻe</td>
<td>Fabaceae</td>
<td>Mucuna gigantea</td>
<td>0.02 ± 10.2</td>
<td></td>
</tr>
<tr>
<td>Morning glory</td>
<td>Convolvulaceae</td>
<td>Ipomoea sp.</td>
<td>0.02 ± 10.4</td>
<td></td>
</tr>
<tr>
<td>Raspberry</td>
<td>Rosaceae</td>
<td>Rubus niveus</td>
<td>0.02 ± 8.1</td>
<td></td>
</tr>
<tr>
<td>Palm</td>
<td>Arecaceae</td>
<td>NA</td>
<td>0.02 ± 8.1</td>
<td></td>
</tr>
<tr>
<td>Unknown 4</td>
<td>Solanaceae</td>
<td>NA</td>
<td>0.02 ± 8.4</td>
<td></td>
</tr>
<tr>
<td><strong>Midstory</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiddlewood</td>
<td>Verbenaceae</td>
<td>Citharexylum caudatum</td>
<td>20.3 ± 16.7</td>
<td></td>
</tr>
<tr>
<td>Ardisia</td>
<td>Myrsinaceae</td>
<td>Ardisia elliptica</td>
<td>5.1 ± 7.5</td>
<td></td>
</tr>
<tr>
<td>Octopus Tree</td>
<td>Araliaceae</td>
<td>Schefflera actinophylla</td>
<td>1.0 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>Lilikoi</td>
<td>Passifloraceae</td>
<td>Passiflora sp.</td>
<td>0.90 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>Java Plum</td>
<td>Myrtaceae</td>
<td>Syzygium cumini</td>
<td>0.70 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>Hau</td>
<td>Malvaceae</td>
<td>Hibiscus tiliaceus</td>
<td>0.60 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>Hiptage</td>
<td>Malpighiaceae</td>
<td>Hiptage benghalensis</td>
<td>0.60 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>Monkeypod</td>
<td>Fabaceae</td>
<td>Albizia saman</td>
<td>0.30 ± 0.48</td>
<td></td>
</tr>
<tr>
<td>Palm</td>
<td>Arecaceae</td>
<td>NA</td>
<td>0.20 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>Unknown 5</td>
<td>NA</td>
<td>NA</td>
<td>0.20 ± 0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
<td>------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>Unknown 6</td>
<td>NA</td>
<td>NA</td>
<td>0.10 ± 0.32</td>
<td></td>
</tr>
<tr>
<td>Unknown 7</td>
<td>NA</td>
<td>NA</td>
<td>0.10 ± 0.32</td>
<td></td>
</tr>
<tr>
<td>Unknown 8</td>
<td>NA</td>
<td>NA</td>
<td>0.10 ± 0.32</td>
<td></td>
</tr>
<tr>
<td><strong>Overstory</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Java Plum</td>
<td>Myrtaceae</td>
<td><em>Syzygium cumini</em></td>
<td>3.0 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>Octopus Tree</td>
<td>Araliaceae</td>
<td><em>Schefflera actinophylla</em></td>
<td>2.0 ± 4.4</td>
<td></td>
</tr>
<tr>
<td>Fiddlewood</td>
<td>Verbenaceae</td>
<td><em>Citharexylum caudatum</em></td>
<td>1.7 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>Strangler fig</td>
<td>Moraceae</td>
<td><em>Ficus sp.</em></td>
<td>0.36 ± 0.50</td>
<td></td>
</tr>
<tr>
<td>Monkeypod</td>
<td>Fabaceae</td>
<td><em>Albizia saman</em></td>
<td>0.18 ± 0.40</td>
<td></td>
</tr>
<tr>
<td>Christmas berry</td>
<td>Anacardiaceae</td>
<td><em>Schinus terebinthifolia</em></td>
<td>0.18 ± 0.60</td>
<td></td>
</tr>
<tr>
<td>Satin leaf</td>
<td>Sapotaceae</td>
<td><em>Chrysophyllum oliviforme</em></td>
<td>0.09 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>Palm</td>
<td>Arecaceae</td>
<td>NA</td>
<td>0.09 ± 0.30</td>
<td></td>
</tr>
</tbody>
</table>
## APPENDIX 3.2

**Table S2.** Native (*), Polynesian introduced (+), and non-native species selected through a co-design, functional trait approach for two restoration treatments. Reproduced from (Hastings et al., 2020).

<table>
<thead>
<tr>
<th>Story</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
<th>Name</th>
<th>Latin Name</th>
<th>Contemporary Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Over-</strong></td>
<td>‘Ohi’a lehua mamo</td>
<td><em>Metrosideros polymorpha</em></td>
<td>leil, hula, ceremony</td>
<td>‘Ohi’a lehua ahihi</td>
<td><em>Metrosideros tremuloides</em></td>
<td>leil, hula, ceremony</td>
<td>Koa</td>
<td><em>Acacia koa</em></td>
<td>lei, wood products</td>
</tr>
<tr>
<td><strong>Mid-</strong></td>
<td>Mai’a iholena lele</td>
<td><em>Musa spp.</em></td>
<td>Food</td>
<td>Maile</td>
<td><em>Alyxia stellata</em></td>
<td>lei</td>
<td>Aweoweo</td>
<td><em>Chenopodium oahuense</em></td>
<td>ceremony</td>
</tr>
<tr>
<td>A’ali’i</td>
<td><em>Dodonaea viscosa</em></td>
<td>lei, hula, medicine</td>
<td>‘Awa</td>
<td><em>Piper methisticum</em>+</td>
<td>drink, ceremony, medicine</td>
<td>Pualoalo</td>
<td>Hibiscus arnottianus*</td>
<td>lei</td>
<td></td>
</tr>
<tr>
<td>Pohinahina</td>
<td><em>Vitex rotundifolia</em></td>
<td>lei, hula, medicine</td>
<td></td>
<td></td>
<td></td>
<td>Māmaki</td>
<td><em>Pipturus albidus</em></td>
<td>tea, medicine</td>
<td></td>
</tr>
<tr>
<td><strong>Under-</strong></td>
<td>Kupukupu</td>
<td><em>Nephrolepis cordifolia</em></td>
<td>leil, hula</td>
<td>Palapalai</td>
<td><em>Microlepia strigosa</em></td>
<td>leil, hula</td>
<td>Nanea</td>
<td><em>Vigna marina</em></td>
<td>leil</td>
</tr>
<tr>
<td>Comfrey</td>
<td><em>Symphytum officinale</em></td>
<td>medicine</td>
<td></td>
<td></td>
<td></td>
<td>Illie’e</td>
<td><em>Plumbago zeylanica</em></td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>‘Aki’aki</td>
<td><em>Sporobolus virginicus</em></td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
<td>Pu’uka’a</td>
<td><em>Cyperus trachysanthos</em></td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Ahu’a wa</td>
<td><em>Cyperus javanicus</em></td>
<td>’awa preparation</td>
<td></td>
<td></td>
<td></td>
<td>Uhaloa</td>
<td><em>Waltheria indica</em></td>
<td>medicine</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 3.3

Table S3. Parameter estimates for correlates of understory cover of agroforestry species subplots from the best fit structural equation model for each of two time periods within the first two years of a transition from non-native forest to agroforest in Hawai‘i.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Estimate</th>
<th>Standard error</th>
<th>z value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 months – 1 year</td>
<td>-0.218</td>
<td>0.097</td>
<td>-2.262</td>
<td>0.024</td>
</tr>
<tr>
<td>Understory cover of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>agroforestry species</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ understory cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of weeds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 year – 1.5 years</td>
<td>-0.308</td>
<td>0.093</td>
<td>-3.308</td>
<td>0.001</td>
</tr>
<tr>
<td>Understory cover of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>agroforestry species</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ understory cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of weeds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Understory cover of weeds ~ canopy cover

1.038  0.753  1.379  0.168
APPENDIX 3.4

SOIL HEALTH ANALYSES

Methods

We took soil samples from each subplot to a depth of 20 centimeters in October 2018 before clearing. We analyzed samples for 11 soil health indicators that were selected for Hawai‘i based on strong ecological grounding (Crow et al., 2021; Hubanks, 2019) (Table S4). Samples taken in 2018 did not contain sufficient soil mass per subplot to run the full suite of soil health indicator analyses at the subplot level. Therefore, we combined samples from two subplots within the same plot, in close geographic proximity to each other, to reach a sufficient mass of soil to analyze all indicators on each sample. We compared values of the soil health indicators in 2018 to published mean values of other sites in Hawai‘i (Crow et al., 2021).
Table S4. Eleven soil health indicators recommended for use in Hawai‘i by (Crow et al., 2021; Hubanks, 2019) and used in this study. Reproduced from (Hubanks, 2019).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Function and Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total organic carbon (%)</td>
<td>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</td>
</tr>
<tr>
<td><strong>Biological Properties</strong></td>
<td></td>
</tr>
<tr>
<td>24 hr CO₂ burst (μg g⁻¹)</td>
<td>Soil respiration in response to readily available substrate; higher value indicates high microbial activity and high-quality organic matter pools</td>
</tr>
<tr>
<td>β-glucosidase (mg p-nitrophenol kg⁻¹ soil h⁻¹)</td>
<td>Proximate microbial metabolism of amino-containing substrate; higher value indicates nutrient, predominantly N, mineralization</td>
</tr>
<tr>
<td>β-glucosaminidase</td>
<td>Potential N supply; higher value indicates bioavailable N forms to support soil productivity</td>
</tr>
<tr>
<td>Mineralizable nitrogen (μg g⁻¹)</td>
<td>Potential N supply; higher value indicates bioavailable N forms to support soil productivity</td>
</tr>
<tr>
<td><strong>Chemical Properties</strong></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>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</td>
</tr>
<tr>
<td>DOC:DON ratio</td>
<td>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</td>
</tr>
<tr>
<td>Hot water extractable carbon (μg g⁻¹)</td>
<td>Readily available metabolic substrate; higher value indicates soluble organic matter and lysed microbial cells that support microbial activity</td>
</tr>
<tr>
<td><strong>Physical Properties</strong></td>
<td></td>
</tr>
<tr>
<td>Water holding capacity (%)</td>
<td>Plant-water relations; higher values indicate improved water storage</td>
</tr>
<tr>
<td>Water stable mega-aggregates (%)</td>
<td>Water infiltration, porosity, aeration; higher values improve retention/transport water, promote root growth, provide habitat for microbes, reduce bulk density, and resist erosion</td>
</tr>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>Infiltration, porosity, and rooting environment; lower values indicate soils that are light, aerated, porous, promote root growth, and more workable</td>
</tr>
</tbody>
</table>
Results

The baseline means of soil health indicators were all within one standard deviation of published means for forests in Hawai‘i (Crow et al., 2021), except for total organic carbon (lower), potentially mineralizable nitrogen (higher), DOC:DON ratio (higher), and water stable mega-aggregates (lower) (Table S5). Because Pu‘ulani is fallow pasture land that has regenerated, we also show mean values of soil health indicators from 12 pasture sites across Hawai‘i (Table S5). The baseline means of soil health indicators at Pu‘ulani were within one standard deviation of the mean for pastures in Hawai‘i for all indicators except 24 hr CO₂ burst (higher), β-glucosaminidase (lower), potentially mineralizable nitrogen (higher), and water stable mega-aggregates (lower). For all indicators except bulk density and DOC:DON ratio, having a higher value is generally considered better soil health. Although the mean values for both land uses provide valuable context, comparisons should be interpreted with caution as some soil health indicators are driven more by soil type than land use, and the sites summarized in the means have different soil types than Pu‘ulani.
Table S5. Data summary of soil health indicators for a non-native forest naturally regenerated on fallow pasture at a site in He‘eia on O‘ahu, Hawai‘i. Means for protected forest and pasture are from 9 and 12 sites across Hawai‘i respectively, which have different soil types, as reported in Crow et al. (2021). Note that the protected forest and pasture sites have different soil types from the study site in He‘eia.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Min</th>
<th>Max</th>
<th>Median</th>
<th>Mean</th>
<th>Protected Forest (n=9)</th>
<th>Pasture (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total organic carbon (%)</td>
<td>2.88</td>
<td>8.33</td>
<td>5.68</td>
<td>5.57 ± 1.22</td>
<td>18.5 ± 7.84</td>
<td>8.58 ± 3.55</td>
</tr>
<tr>
<td>24 hr CO₂ burst (μg g⁻¹)</td>
<td>185.7</td>
<td>551.9</td>
<td>324.5</td>
<td>341.8 ± 85.1</td>
<td>274.5 ± 126.7</td>
<td>177.8 ± 69.5</td>
</tr>
<tr>
<td>β-glucosidase (mg p-nitrophenol kg⁻¹ soil h⁻¹)</td>
<td>57.7</td>
<td>148.8</td>
<td>91.4</td>
<td>94.5 ± 22.6</td>
<td>117.3 ± 32.2</td>
<td>131.1 ± 37.6</td>
</tr>
<tr>
<td>β-glucosaminidase</td>
<td>39.7</td>
<td>102.2</td>
<td>65.5</td>
<td>65.8 ± 16.8</td>
<td>81.3 ± 26.4</td>
<td>90.9 ± 19.9</td>
</tr>
<tr>
<td>Potentially mineralizable nitrogen (μg g⁻¹)</td>
<td>83.3</td>
<td>406.4</td>
<td>266.6</td>
<td>258.7 ± 83.1</td>
<td>152.8 ± 76.2</td>
<td>54.3 ± 15.1</td>
</tr>
<tr>
<td>pH</td>
<td>5.80</td>
<td>7.38</td>
<td>6.71</td>
<td>6.66 ± 0.36</td>
<td>6.04 ± 1.17</td>
<td>6.51 ± 0.32</td>
</tr>
<tr>
<td>DOC:DON ratio</td>
<td>8.72</td>
<td>16.7</td>
<td>11.1</td>
<td>11.3 ± 1.62</td>
<td>2.68 ± 0.45</td>
<td>17.0 ± 13.9</td>
</tr>
<tr>
<td>Hot water extractable carbon (μg g⁻¹)</td>
<td>301.52</td>
<td>1843.6</td>
<td>1312.7</td>
<td>1208.5 ± 485.8</td>
<td>5245.0 ± 4085.6</td>
<td>1001.1 ± 444.0</td>
</tr>
<tr>
<td>Water holding capacity (%)</td>
<td>102.7</td>
<td>144.6</td>
<td>115.6</td>
<td>117.8 ± 9.48</td>
<td>136.7 ± 40.3</td>
<td>97.9 ± 23.8</td>
</tr>
<tr>
<td>Water stable mega-aggregates (%)</td>
<td>2.28</td>
<td>21.0</td>
<td>11.0</td>
<td>10.5 ± 3.61</td>
<td>73.2 ± 15.0</td>
<td>79.9 ± 12.7</td>
</tr>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>0.49</td>
<td>0.79</td>
<td>0.64</td>
<td>0.65 ± 0.06</td>
<td>0.54 ± 0.20</td>
<td>0.80 ± 0.20</td>
</tr>
</tbody>
</table>

Acknowledgements

Susan Crow, Christine Tallamy Glazer, Angelica Melone, and Elaine Vizka helped with soil sampling and analyzed the soil health indicators. The He‘eia National Estuarine Research Reserve provided funding for the soil health analyses.
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ABSTRACT
Agroforestry is often promoted as a multi-benefit solution to increasing the resilience of agricultural landscapes. Yet, there are many obstacles to transitioning agricultural production systems to agroforestry. Research on agroforestry transitions often focuses on why farmers and land managers chose to adopt this type of stewardship, with less focus on the political context of practitioner decisions. We use the case study of agroforestry in Hawaiʻi to explore how agroforestry transitions occur with particular attention to politics and power dynamics. Specifically, we ask, what factors drive and/or restrain transitions to agroforestry and who is able to participate. We interviewed 38 agroforestry practitioners in Hawaiʻi and analyzed the data using constructivist grounded theory. We then held a focus group discussion with interview participants to share results and discuss solutions. Practitioners primarily chose agroforestry intentionally for non-economic and values-based reasons, rather than as a means to production or economic goals. Agroforestry practitioners face a similar suite of structural obstacles as other agricultural producers, including access to land, labor, and capital and ecological obstacles like invasive species and climate change. However, the conflict in values between practitioners and dominant institutions manifests as four additional dimensions of obstacles constraining agroforestry transitions: systems for accessing land, capital, and markets favor short-term production and economic value; Indigenous and local knowledge is not adequately valued; regulatory, funding, and other support institutions are siloed; and not enough appropriate information is accessible. Who is able to practice despite these obstacles is tightly linked with people’s ability to access off-site resources that are inequitably distributed. Our case study highlights three key points with important implications for realizing just agroforestry transitions: 1) practitioners transition to agroforestry to restore ecosystems and reclaim sovereignty, not just
for the direct benefits; 2) a major constraint to agroforestry transitions is that the term agroforestry is both unifying and exclusionary; 3) structural change is needed for agroforestry transitions to be just. We discuss potential solutions in the context of Hawai‘i and provide transferrable principles and actionable strategies for achieving equity in agroforestry transitions. We also demonstrate a transferrable approach for action-oriented, interdisciplinary research in support of just agroforestry transitions.
INTRODUCTION

The triple threat of climate change, biodiversity loss, and food insecurity is a major challenge to food system resilience. Re-localization of food systems, shortening supply chains, and adding redundancy to markets can enhance resilience of distribution and market channels (Tendall et al., 2015). At the same time, calls for changes in agricultural production to be regenerative and climate smart abound (Newton et al., 2020; Petersen-Rockney et al., 2021). How we produce food matters for food system resilience.

Agroforestry is widely promoted as a resilience strategy. The term agroforestry was coined in the late 1970’s by researchers and development professionals, primarily from high income countries, to describe land management systems that simultaneously increase the productivity of landscapes while also reducing environmental degradation (Bene et al., 1977). Agroforestry has come to encompass farm level technical practices that integrate woody plants and crops and/or livestock for environmental and practical benefits (NRCS, 2013), Indigenous stewardship practices based in ecomimicry (Ticktin et al., 2018; Winter et al., 2020), and a landscape approach “to removing the conceptual and institutional barriers between agriculture and forestry” (van Noordwijk et al., 2018). Subsequently, a large body of literature documenting the ecosystem services of agroforestry systems and optimizing system design for production and environmental benefits followed. Research has thus shown forms of agroforestry can diversify livelihoods (Miccolis et al., 2019), conserve biodiversity (Kremen and Merenlender, 2018), and increase pollination services (Bentrup et al., 2019), sediment retention, and nutrient cycling (Torralba et al., 2018). Agroforestry is considered a natural climate solution (Griscom et al., 2017) as these practices also contribute to carbon sequestration (Chapman et al., 2020) and social-ecological resilience (Quandt et al., 2017; Ticktin et al., 2018), or the ability of a system to continue to function over time despite disturbances (Berkes et al., 2002). As a result, institutions ranging from local governments to international agreements are increasingly including agroforestry as a component of their social-ecological resilience strategies (Rosenstock et al., 2019; Griscom et al., 2020), including National Adaptation Plans and Nationally Declared Contributions (Fortuna et al., 2019; Meybeck et al., 2019).

Yet, how to increase agroforestry on landscapes to meet these targets remains a question. A significant body of research has explored existing farmers’ decisions to start practicing, or adopt, agroforestry (Pattanayak et al., 2003; Mercer, 2004; Meijer et al., 2015; Amare and Darr, 2020).
Research has largely focused on econometric modeling, showing that producers adopt agroforestry to meet economic goals or to circumvent obstacles like limited labor or depressed prices (Amare and Darr, 2020). For example, when a tree crop price declines, producers may start growing a short-term understory crop between their tree rows to augment their income. Fewer studies have intentionally examined the non-economic reasons for deciding to practice agroforestry, yet studies that do can uncover important narratives (Decré, 2021). The concept of adoption has conceptual and operational limitations, namely that it is an oversimplified model of change and detecting adoption may not be as valuable as understanding the context of the decision to adopt (Glover et al., 2016, 2019). Instead, we use ‘agroforestry transitions’ to describe the multi-year process of land use change from active or fallow simplified agriculture or non-native dominant forest to agroforestry (Ollinaho and Kröger, 2021). At the site level, agroforestry transitions can occur when an existing land steward changes their practices, or a steward gains new access to land and begins practicing agroforestry. These transitions are socially and ecologically complex, often involving a succession of different financing mechanisms, labor sources, and plant and animal species over a number of years. Enabling agroforestry transitions that last therefore requires a better understanding of the drivers and constraints to practitioners’ ability to not only make an initial change in practices, but also to continue to practice throughout the multi-year transition process.

Constraints to agroforestry transitions are considerable. Some of the most significant obstacles to agroecological transitions include difficulty accessing land, labor, and start-up capital (Anderson et al., 2019). These obstacles are often more acute for agroforestry practitioners because the trees, shrubs, and other perennials in agroforestry systems take longer to mature and provide a return on investment than annual crops. Therefore, secure, long-term tenure can be a major obstacle to agroforestry (Lawin and Tamini, 2019). High start-up costs and longer returns on investments makes persisting after establishment challenging, and this can be a significant source of risk for practitioners (Buttoud, 2013). Accessing plant material is another challenge as agroforestry systems often include native and other underrepresented plant species, many of which are not readily accessible (Lillesø et al., 2018). Lack of financial incentives, limited marketing for agroforestry products, and lack of knowledge can also be barriers (Sollen-Norrlin et al., 2020).
Although the above research is important for understanding and promoting agroforestry transitions, much of the literature neglects the unequal power dynamics shaping who is able to participate in transitions. For example, focusing on the experience of individual landowners can downplay the power relations that shape who can be a land manager and assumes that all farmers have the power to choose sustainable forms of agriculture (Calo, 2020). A major gap is the need to consider the political ecological context of transitions to agroforestry. This includes how politics and power of the global food system affect agroforestry transitions (Ollinaho and Kröger, 2021). A more power centered analysis of agroforestry transitions can, for example, illuminate how gender disparities in knowledge transfer affect participation (Duffy et al., 2020), how the power of a state agency can constrain local participation (Islam et al., 2015), how agroforestry interventions can alter labor distribution and displace existing social and economic gains (Schroeder, 1999), or how sustainable intensification narratives can constrain equitable outcomes for smallholders (Nasser et al., 2020). Political ecology approaches that critically examine tenure rights and gender and class power can also reveal how, for example, agroforestry transitions contribute to dispossession and private accumulation, and thus become exclusive (Schroeder and Suryanata, 1996). Additionally, access to political decision-making processes and ideology in agricultural research and development limit agroecological transitions (Isgren et al., 2020), but have received less attention in research on agroforestry transitions. Considering the institutional and social factors that influence agroforestry transitions remains a major gap (Rocheleau, 1998; Molina, 2013; Meek, 2016).

We use a case study of agroforestry in Hawai‘i to examine the politics and power dynamics of agroforestry transitions. Indigenous agroforestry was widespread in Hawai‘i for nearly a millennia prior to European colonization (Kurashima et al., 2019) and was characterized by a diversity of perennial understory and tree crops that were used for food, medicine, ceremony, tools, clothing, and building (Kurashima and Kirch, 2011; Lincoln, 2020). Yet, following European contact in 1778, the Kānaka ʻŌiwi (Native Hawaiian) population declined an estimated 84% by 1840 (Swanson, 2016). In 1848, a process called the Māhele (division of land), led to land privatization and accumulation by non-Hawaiians (Kame‘elehiwa, 1992). Sugar and pineapple plantations came to dominate the agricultural and political landscape, and, in 1893, a group of American-backed white businessmen overthrew the Hawaiian monarchy. As a result, today Hawai‘i for the most part lacks a tradition of smallholder farms growing diversified crops
This legacy combined with the high costs of land, labor, water, and other structural infrastructure significantly impedes the regeneration of diversified agriculture in Hawai‘i (Suryanata, 2002; Heaivilin and Miles, 2018). Now, less than 8% of the state’s agricultural zoned lands are used for growing crops, most products are exported (Melrose et al., 2015; USDA-NASS, 2019), and nearly 88% of food is imported (Loke and Leung, 2013). In response, the state department of forestry, state resilience office, and other public and private institutions have included agroforestry in their resilience strategies, and public discourse in support of agroforestry as a multi-benefit solution is building (Caulfield, 2019).

We interviewed agroforestry practitioners in Hawai‘i to understand how agroforestry transitions are occurring today in this context. We asked: 1) why do people transition to agroforestry, 2) what are their obstacles, and 3) who is able to participate? We find that people’s motivations for transitioning to agroforestry are largely non-economic and values-based – most practitioners chose agroforestry intentionally as a form of ecological restoration and/or cultural reclamation, rather than as a means to production or economic goals. The contested values between practitioners and dominant institutions manifests as a suite of obstacles that lead agroforestry practitioners to fall through the cracks, and subsequently to have insufficient access to appropriate information. We highlight how resources external to practitioners and sites - both financial and social capital - are what allow practitioners to circumvent the many obstacles they face, which constrains equitable participation. Finally, we discuss potential solutions to creating more just pathways to agroforestry in this context and transferable lessons for similar transitions.

METHODS

Sampling Frame

We conducted nonprobability sampling of agroforestry sites in Hawai‘i. We define agroforestry as a continuum of systems that integrate woody plants and crops or livestock (or other tended and harvested plant or animal species) (Hastings et al., 2020). We included people practicing agroforestry for subsistence and/or non-economic benefits as well as practitioners who sell products, including those designated as farms by the USDA, defined as any size plot of land that produces $1,000 or more of agricultural products per year. According to the 2017 Census of Agriculture, 347 of the total 7,228 farms in the state indicated that they practice at least one of the following types of agroforestry: alley cropping, silvopasture, forest farming, riparian forest.
buffers, or windbreaks (USDA-NASS, 2019). In the 2012 Census of Agriculture, the question about agroforestry only included two practices – alley cropping and silvopasture – and 38 farms in Hawai‘i reported having these practices (USDA-NASS, 2019). We aimed to sample from practitioners who answered yes to the 2017 Census question; who completed the Census and practice some form of agroforestry but answered no to the Census question (e.g., because they did not know or identify with the practice names used in the Census questionnaire); and those excluded from the Census (e.g., because they did not sell enough product to qualify as a farm).

We developed an initial list of 15 businesses, non-profit organizations, and subsistence farmers practicing some form of agroforestry from informal interviews conducted between August 2016 and June 2020 with farmers, farmer support personnel, and land managers. We then used purposive sampling to request interviews, stratifying by agroforestry practice type and island. We used snowball sampling with initial interviewees to increase the diversity of the participant pool (Bernard, 2018). We also emailed eight extension agents to help identify additional practitioners, which produced a total of three additional interviewees. We continued interviewing participants until we reached saturation, or the point where no new themes arose from additional interviews (Bernard, 2018), in this case 31 interviews.

**Interviews and Focus Group**

We used a qualitative, inductive approach to develop a relational understanding of both individual and contextual factors influencing agroforestry transitions in Hawai‘i. We used information from informal interviews conducted between August 2016 and June 2020 with farmers, farmer support personnel, and land managers in Hawai‘i and a review of the academic literature on agroforestry transitions to develop a semi-structured interview guide. The interview guide included questions about how the practitioner came to steward land in that place using agroforestry practices, what was involved in the transition to agroforestry, what their agroforestry practice is like today, why they integrate trees, what challenges they face, and what would help them and others overcome the challenges to transitioning to agroforestry.

We interviewed a total of 38 agroforestry practitioners representing 31 sites across five of the main islands of Hawai‘i; seven interviews included multiple stewards of the same site. We held interviews via Zoom (due to COVID-19 safety restrictions) from August 2020 to May 2021. Interviews followed the open-ended guide described above, with similar questions and probes.
for each interview. At the end of each interview, we collected demographic information: highest level of formal education, age, gender, and race/ethnicity. Interviews lasted between 50 minutes and two hours. We recorded the interviews on a local computer using Zoom.

We used the software otter.ai to transcribe the interviews, and then we checked and edited each transcript for accuracy. Next, we imported text transcriptions into the NVivo data management and analysis software package. We used constructivist grounded theory analysis to code themes on the motivators for, and obstacles to, agroforestry practices as well as the ways in which practitioners are circumventing these obstacles (Charmaz, 2014). A single coder (Z.H.) performed the initial coding. Subsequently, the other study authors evaluated the codes, discussed disagreements with the initial coder, and quotes were re-coded as necessary. We recorded all coding procedures to create transparency. To check the coding scheme, we used member checking and looking for negative evidence (Bernard, 2018). We also extracted quantitative data from the interviews to create tables of site and practitioner characteristics.

Finally, we held a focus group meeting via Zoom with a total of seven practitioners from four sites who participated in the first round of interviews. The goal of this meeting was to share preliminary findings with interview participants, facilitate reflection, and discuss possible solutions and pathways forward. This step facilitated knowledge co-creation and social learning among practitioners (Eelderink et al., 2020).

RESULTS
Agroforestry practices and practitioners are diverse

The 38 practitioners we interviewed ranged in age, gender, and ethnicity. Practitioners ranged from 25-75 years old, with a median age of 46. Most (68%) identified as male. Practitioners who self-identified as Kānaka ʻŌiwi (Native Hawaiian) made up 50% percent of the interviewees. Individuals identifying as white alone were the next most represented group (37%), followed by Asian and Pacific Islander (not Kānaka ʻŌiwi) (13%).

The practitioners represented 31 sites - families, businesses, or non-profit organizations with land access. The median land area each site tends using agroforestry is 10 hectares, excluding one site that tends over 405 hectares. Over half of the sites are on Hawai‘i Island. Sixty-one percent of sites own or co-own the land they steward. Of the 39% of sites that rent land, most of them (67%) lease from the state’s largest private land owner, Kamehameha.
Schools. The majority of practitioners gained access to former plantation agriculture or ranching lands that were fallow and transitioned from non-native grasses, shrubs, and/or trees to agroforestry. Only four practitioners had been practicing a less diverse type of agriculture (e.g., monoculture vegetable or tree crop) on the same parcel before transitioning to agroforestry. Two sites transitioned actively managed pasture land to agroforestry by planting trees (i.e., silvopasture). Three practitioners inherited family legacy lands that already had agroforestry.

The agroforestry practices at each site are diverse. Half of all sites integrate trees and other plants at the plot level, meaning multiple plants are grown together in one field (e.g., multi-story cropping, alley cropping, or food forest) (Fig. 4.1). Other sites integrate woody and non-woody plants at the field or margin levels (e.g., windbreaks). All sites intentionally grow at least 10 species of plants. The most common plants grown for harvest include canoe plants (plants first brought to Hawai‘i by Polynesian navigators) such as ‘ulu (*Artocarpus altilis*), mai’a (*Musa* sp.), ‘awa (*Piper methysticum*), and kalo (*Colocasia esculenta*); introduced “cash” crops including coffee (*Coffea* sp.) and cacao (*Theobroma cacao*); and native forest plants such as māmaki (*Pipturus albidus*), koa (*Acacia koa*), and ‘iliahi (*Santalum* sp.). Nine sites integrate animals into their system, including cattle, sheep, goats, chicken, ducks, and fish.
Figure 4.1. Practitioners in Hawai‘i integrate trees and shrubs with other plants and animals in agroforestry systems ranging from cacao and windbreak systems, to multi-story forests including a range of native and non-native plants for multiple products, to silvopasture with native trees and cattle. Pictured here is an example of a multi-story agroforestry plot in the establishment phase at Kākoʻo ʻŌiwi, Heʻeia, Oʻahu. Key visible plants include a native, culturally important tree, wiliwili (*Erythrina sandwicensis*); Polynesian introductions ti (*Cordyline fruticosa*) and maiʻa iholena lele (*Musa* sp.; banana); and an introduced medicinal plant, comfrey (*Symphytum officinale*).

Motivations relate to practitioners’ values and the direct benefits of agroforestry

Each person we talked with gave a combination of reasons for transitioning to agroforestry that related to their values and the direct or practical benefits of agroforestry (Table 4.1). The first reasons most people gave for transitioning to agroforestry related to two values-based
dimensions: 1) to restore relationships with ʻāina (land), culture, and ancestors, and 2) to strengthen local communities. The third dimension of themes was the direct or practical benefits of agroforestry. Although not all of the values-based themes are linked exclusively to agroforestry, each practitioner expressed a suite of themes, including agroforestry-specific reasons. The combination of more general themes (e.g., feeding community) and agroforestry-specific themes (e.g., bring the forest back), are what led a practitioner to agroforestry specifically. In the sections that follow, we discuss the themes within each dimension of motivators in detail (Table 4.1).
### Table 4.1. Factors motivating people to transition to agroforestry in Hawaiʻi.

Some motivators represent values and visions for change that could be achieved through multiple forms of agroecology or sustainable agriculture, not just agroforestry. Practitioners also gave reasons that related to agroforestry specifically (denoted with asterisk). Themes are listed in order of most referenced.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Theme</th>
<th>Illustrative Quote</th>
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<tr>
<td><strong>Values</strong></td>
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| Restore relationships to ʻāina (land), ancestors, culture | reverse damage of plantation agriculture and ranching | "So, what motivated us to take on a farming practice like this, part of that for me always goes back to the ʻōlelo noʻeau [Hawaiian proverb], I ka wā ma mua, I ka wā ma hope, the answers to the future lie in the past...And so I believe that in order for us to look at planning for our future, we need to, at the very least, understand our history and learn from it. Or in what I believe now is more to go back to most of it..."
| | kuleana (responsibility) to ʻāina | |
| | the template was created by our ancestors* | |
| | bring the forest back* | |
| | reclaim identity* | |
| | have materials for cultural practices* | |
| | it's for future generations* | |
| Strengthen local communities | feed our community | "We're trying to elevate our community to the status of being able to be autonomous, to be able to be sovereign. And so we have to start with growing food."
| | community's health and wellness | |
| | grow young people | |
| | create more jobs, change stigma | |
| | create a model and inspire others | |
| **Direct benefits** | | |
| Direct or practical benefits of agroforestry | personal health and wellness* | “I think that's what really drove [our] method is really having a really biodiverse system, having different personalities helping each other out. So, if you put a tree out by itself to take on all the different elemental things like the wind or rain, the environment, the ungulates, the chances of that one tree out there alone surviving is not as high as the one that is planted together with family. So we’ll look at the ʻohana [family] environment, you get your moʻopuna [grandchild], you get the ʻōpio [child], you get the makua [parent], the kupuna [grandparent]; your whole family protecting the most vulnerable one...”
| | need multiple types of products* | |
| | build soil fertility and health* | |
| | strength of planting an ʻohana (family)* | |
| | protect the crop* | |
| | aesthetic value* | |
| | less maintenance* | |
| | hold back invasive plants and weeds* | |
| | make the most of steep areas and areas between trees* | |
| | it's better to work in the shade* | |
| | diversify income* | |
| | prevent erosion* | |

* Indicates that practitioners discussed this motivator as a reason for tree-based practices specifically.
Values: Restore relationships

The first dimension of values-based motivators for agroforestry was to restore relationships to ʻāina (land), culture, and ancestors (Table 4.1). The most referenced theme in this dimension was to reverse the damage caused by plantation agriculture and ranching. Practitioners lamented how “the cattle system has decimated this valley”, “how abused the soils were”, that “what humans have been doing for a long time is taking, taking, taking”, and that “we’re in the middle of the sixth great extinction”. The damage they saw was not just environmental. As one practitioner recounted,

“...what I saw was a lot of social injustice, and maybe even in a racial context. And I saw that pretty much against Hawaiians, and that was very disturbing to me. And so that as my ends, have led me to agroforestry as a means.”

Many practitioners saw the links between environmental and social damage as systemic, resulting from colonialism and capitalism. Therefore, their practices were a way to not only “regenerate ʻāina” and “solve a whole bunch of [social] problems that were entrenched in [our community]”, but also to assert their values. For example, one practitioner articulated how the drive to accumulate financial wealth that is dominant in “American Western culture” is a major cause of damage and conflicts with their values. Their goal is “to take it back the other way.”

Thus, another theme practitioners expressed was being motivated by the need to take back “kuleana [responsibility] to ʻāina”, restoring reciprocity with land and the environment rather than valuing money and extraction. One practitioner identified this as their “conservation ethic”. They described how they use regenerative agriculture because it allows them to conserve open space, native plants, and water outside of protected areas. Another practitioner identified that they were initially motivated to farm this way by the “back to the land movement”. One practitioner, whose land had mixed native-non-native forest on it when he and his wife bought it, recounted how they came to practice “conservation agriculture”,

“Well see, originally we were gonna plant corn. We were gonna be like regular dirt farmers [laughter] [...] But then we realized that we didn't want to destroy [the forest]. It was so peaceful and beautiful. We didn't want to destroy it. [...] We are proud of what we
do, and we do it because it's a way of giving back and preserving the environment. As a Hawaiian, I believe that I'm doing the right thing. Because that's what I was taught by my elderly people. You don't get rich off what we're doing. But it's rewarding.”

Rather than allowing profit to dictate their practices, this story illustrates how many practitioners prioritize their kuleana (responsibility) to ‘āina first. This practitioner, like many others, chose to restore a reciprocal relationship with ‘āina and culture, rather than remain disconnected from the negative environmental effects of conventional agriculture. Similarly, another practitioner articulated, “We like to believe there's a balance, there's a way we can be growing the food and taking care of the forest at the same time; we don't need to clear the forest just to grow the food, we keep doing both.”

Relatedly, some values rooted in Indigenous culture and ‘ike kupuna (ancestral knowledge) motivated people to practice agroforestry specifically, rather than another form of regenerative agriculture. First, was the theme that “the template was created by our ancestors”. For example, practitioners described going through historical records to find that “historically, the space was known to have a very large food forest system, for lack of a better term”. The template for agroforestry already existed pre-colonization. Practitioners articulated how they wanted to use this template because of the immeasurable value of the knowledge held in these systems, pointing out, “our people have been collecting data for 1000s of years”. Trying to re-establish these systems was therefore an easy decision: “if it's not broken, don't change it”. Second, a reason for practicing agroforestry following ‘ike kupuna was “to bring back a part of that history” and to reclaim Kānaka ʻŌiwi identity from colonialism and plantation agriculture. One practitioner described how the sugarcane plantations were “a really decorated piece of history” in their childhood. They saw their access to land now as an “opportunity to change that historical fabric” and “reaffirm our identity”. Similary, another practitioner echoed, “I'm learning, or sometimes I think that I'm re-learning, how to be a mahiʻai [farmer], because, you know, we have these agricultural roots as kānaka.”

Next, many practitioners articulated that they wanted to bring the forest back. This was described again as a response to degradation of ranching and plantation agriculture, and a way to reconnect with ‘āina. One practitioner expressed that when they were able to buy land, “it was an opportunity to try and change what had happened and go back to a system that was more
sustainable; so the whole drive behind this project is to re-establish the forest.” Their business views sustainable harvest of timber and non-timber forest products as a way to make forest restoration economically viable. Speaking about native forest restoration he said, “That’s the goal; and the goal is not having to go out and beg somebody for money to do it.”

Relatedly, another motivation for agroforestry was to have materials for cultural practices. One practitioner grew forest plants in partnership with a hālau hula (Native Hawaiian dance school), so that they could limit the amount they harvest from remnant native forests above their site. Bringing back the plants in this case was not just about the harvest. The practitioner described how increasing access to the plants was also about bringing back culture, “Kumu [Teacher] always says that some of the holier chants that we do there hasn’t been heard in that area for maybe a couple 100 years.” Practitioners were themselves, or had relationships with, carvers, hula practitioners, lei makers, and weavers. The wood, gourds, ferns, flowers, and other plants that practitioners grow reinforces their ability to restore relationships with ʻāina, ancestors, and culture.

Finally, practitioners described practicing agroforestry because “it’s for future generations”. One practitioner described using Indigenous agroforestry to “make sure that this mountain will be able to gather and retain water for our great, great, great, great grandkids right down the line.” Many of the trees that practitioners grow, like ʻiliahi (sandalwood; Santalum sp.), take at least 30 years to mature. Instead of putting pressure on himself to have an abundant agroforest in his lifetime, one practitioner said this work requires a “generational mindset”.

Values: Strengthen local communities

The second dimension of values-based motivators for agroforestry practices that emerged from the interviews was to strengthen and elevate local communities (Table 4.1). The first theme in this dimension was choosing agroforestry to “feed our community”, which was articulated by over half of the practitioners we spoke with. Although practitioners could feed their communities through other types of agriculture, many practitioners expressed that they chose agroforestry as a way to produce a diversity of food, over a long time. For example, agroforestry was the specific way one practitioner chose to feed their community because, “the agroforestry that we do is
mostly just trying to think long term, like, how do you feed your community longer than just for one grant cycle?"

Second, and interrelated with the first, practitioners were motivated by their community’s health and wellness. For example, one practitioner expressed that they practiced agroforestry because, “healthy land and healthy people, can't really separate those two things”. Another practitioner explained how agroforestry aligns with their goals to support healthy communities:

"...the la'au lapa'au [medicine] aspect, like seeing that the ‘āina [land], the forest, is our medicine, is our pharmacy. That is a big part of what we do. A lot of us might think agroforestry is just agriculture and forests, but it's also medicine. Right, because a lot of those food crops like mountain apple, for example, is a medicine itself."

Next, practitioners expressed how they were motivated to were motivated by youth development and job creation. One practitioner said, “my motivation is always children” and another, “...we see the growing of food as a means to growing young people in our community.” A Kānaka ʻŌiwi practitioner shared, “working and being conditioned to do only certain jobs for local boys, I wanted to kind of change that stigma.”

Finally, almost a third of practitioners were motivated to inspire others and to create a model of how to practice agroforestry today. For several practitioners this involved inspiring others to grow food at home. For example, one practitioner explained that "what I'm focused on building here, on my land, is a demonstration center, an educational center for tropical subsistence farming." Others were more focused on larger models. One practitioner said, "the mission was to create a model to revitalize agriculture in Hawai‘i that was economically viable and could be scaled." Although many of these same practitioners identified that a template for agroforestry was created by their ancestors, they also experienced the challenges to reclaiming this history and knowledge in the current political-economic context and wanted to create a model to make it easier for others.

**Direct or practical benefits**

While it was common for practitioners to open with how their values motivated them, many also went on to share motivations related to the direct benefits of agroforestry. First,
almost half of practitioners discussed how they practice agroforestry for their own health and wellness. Practitioners shared testimonials such as, “I have not had to go to a therapist or a psychologist ever since I started agroforestry.” They also described how mixed forest systems “nurture us on a spiritual and emotional level”, “really ground you”, are “so peaceful”, and “make us feel super good”. Other practitioners expressed, “I'm definitely motivated to plant more trees just because I like trees”, “we're tree people”, and “I just feel safe in a forest”.

Second, almost half of practitioners expressed that they were motivated by the need for multiple types of products. Practitioners talked about how agroforestry, especially traditionally in the Pacific and other parts of the world, is “out of need”, for example, for food, medicine, fiber, and fuel. Agroforestry also allows practitioners to “diversify the food that we’re growing” and incorporate “succession harvesting”.

Third, nearly half of practitioners chose agroforestry to build soil fertility and health. Many practitioners talked about using trees to produce organic matter to incorporate into the soil, for example through “chop and drop”. Some practitioners incorporated animals or nitrogen fixing trees to reduce the need to buy expensive fertilizers. In this way, agroforestry was a means to overcome an obstacle to conventional agriculture.

Next, practitioners described choosing agroforestry because of the strength of planting an ‘ohana (family). For example, one practitioner observed about their trees, “when they’re with each other they thrive as opposed to being out in the pasture alone.” Another practitioner acknowledged this as the importance of “symbiotic relationships”. A few practitioners discussed how they incorporate a diversity of perennial plants, especially natives, to host beneficial insects for pollination and pest control.

Relatedly, practitioners explained that they incorporate trees to protect a crop, particularly through wind protection and shade. Although most practitioners started stewarding land with the intent to transition the site to agroforestry, a few practitioners made the decision later in their stewardship of a site. Two practitioners cited that their values led them to initially grow a single perennial or culturally important crop (i.e., cacao or kalo), yet a few years into stewarding, severe wind damage to the crop led them to incorporate trees as protection. As the cacao farmer explained, “So the agroforestry component of it, on the farming side, really came totally out of necessity. It wasn't like I set out to build a forest, I had to learn that I needed a forest.”
Finally, practitioners described choosing agroforestry as a means to decreasing labor costs and maximizing productivity, both indirect economic motivations. One theme was that agroforestry requires less maintenance, in large part because tree cover decreases growth rates of weeds. For example, when asked why did you decide to integrate trees and crops, one kava (*Piper methysticum*) grower explained, “My kava buyer asks me that question all the time. He's like, ‘Oh, they grow faster in the full sun.’ Well, they do. But there's a lot more maintenance.” Similarly, another theme echoed by several practitioners was that, “agroforestry is definitely part of a strategy to hold back invasive plants and weeds in some areas.” A third theme was to make the most of steep areas not suited for annual crops and areas between trees in existing orchards. A practitioner who transitioned an orange orchard to agroforestry described how the previous steward had planted the tree rows too far apart, wasting sunlight, and creating more area to mow. She explained how she decided to transition to agroforestry, “I'd rather put something there, but it's not quite enough to plant another row of orange trees, so it's good for rotation of bananas, or pineapples, or some of those shorter term crops that never get too big.”

These last three themes show how some practitioners chose agroforestry as a means to circumvent obstacles like limited labor or unfavorable site conditions and achieve economic productivity rather than choosing agroforestry as a purposeful destination itself. Only one practitioner cited that they transitioned to agroforestry to diversify their income, a direct economic benefit.

**Agroforestry practitioners face common and unique constraints**

Some of the obstacles interviewees expressed are not unique to agroforestry; they are shared by other agricultural producers in Hawai‘i, especially small farmers. Top themes of structural obstacles included access to land, labor, capital, and infrastructure. For example, the high cost of living, regulations that prevent living on agricultural land, agricultural theft, and the pressure to prove value relative to real estate development were important challenges throughout agroforestry transitions. Practitioners expressed that the lack of policymaker support for agriculture and forestry challenged their ability to establish and persist. Failure of the government to enforce regulations, for example around environmental protections for land clearing which can cause erosion and poor water quality on practitioners downstream, was another challenge.
Practitioners also identified common ecological and practical management obstacles. The top referenced theme was nonnative or invasive plants and weeds. As one practitioner lamented, “the more we clear, the more we have to maintain”. Several practitioners who had more established agroforestry practices felt burdened by the risk of new pests and diseases being introduced and viewed this as a failure of government regulation. Disturbance from pigs and deer was another obstacle at all stages of transitions, requiring many practitioners to invest in costly fencing. Lack of water rights and poor soil quality, legacies of the plantation era, especially challenged practitioners in the establishment phase. Additionally, climate change, drought, wind, floods, and fire were key obstacles.

However, our interviews revealed that agroforestry practitioners in Hawaiʻi face an additional set of unique constraints. As described in the previous section, most interviewees chose agroforestry intentionally, primarily for values-based reasons rather than as a means to achieving production or economic goals. These values conflict with the dominant values, institutions, and systems of resource access in Hawaiʻi today causing practitioners to “fall through the cracks” and subsequently ask, “where do we find all of this information?” (Fig. 4.2). In the following sections, we describe the four dimensions of themes of agroforestry-specific obstacles that emerged from the interviews (Table 4.2).
Figure 4.2. Practitioners in Hawai‘i were motivated to practice agroforestry largely by their values, but also the direct or practical benefits of agroforestry (green box). These motivations, and the resulting diverse agroforestry systems, directly conflict with the dominant values, institutions, and systems of resource access, which produces a suite of agroforestry-specific obstacles (red box). Institutions include local, state, and federal agencies and organizations that support and regulate practitioners as well as social norms and worldviews. For themes and illustrative quotes, see Table 4.1 (motivators) and Table 4.2 (agroforestry-specific obstacles).
## Table 4.2. Obstacles specific to agroforestry that practitioners in Hawai‘i face.

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<th>Dimension</th>
<th>Theme</th>
<th>Illustrative Quote</th>
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<tbody>
<tr>
<td><strong>We fall through the cracks</strong></td>
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<tr>
<td>Systems for accessing land, capital, and markets favor short-term production and economic value</td>
<td>it's not easy to find those kinds of leases</td>
<td>&quot;There's not many people that want to take up projects like this, because it doesn't make the economics...So it's almost like you got to work with whoever can provide you with the capital structure to really even get going. If I could do this in my own backyard, that would be ideal.&quot;</td>
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<td>having the start-up capital</td>
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<td></td>
<td>keeping up with maintenance and expenses while waiting for long-term benefits</td>
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<td>pressure to turn a profit in the short term</td>
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<td></td>
<td>lack of supply chain infrastructure</td>
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<td>it's hard to do education and production</td>
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<td></td>
<td>being tied to fiscal year deliverables</td>
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<tr>
<td>Indigenous and local knowledge is not adequately valued</td>
<td>local practitioner knowledge is not valued</td>
<td>&quot;They basically have these cookbook recipes on how to responsibly manage land and deal with erosion and all of that. And some of its good, but I think it just takes the creativity and some of the experience and maybe some of the wisdom out of managing something, some of the relationship, all of that stuff that's hard to touch, and put your finger on but those are maybe more important than just like, 'everything must be 14 feet apart and here's your list of appropriate species'.&quot;</td>
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<td>agroforestry is viewed as a technical practice</td>
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<td>money is what talks</td>
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<tr>
<td>Institutions are siloed</td>
<td>polarization between conservation and agriculture</td>
<td>&quot;When you're trying to get ag exemptions, and it doesn't look clear to them like a pasture, you know, it's not clear to them that this is an orchard because agroforestry doesn't look like that. Agroforestry in the true form that we practice looks like a mess, like rows that are in a mess with mowed rows in between kind of. So, they just don't know what's agroforestry, they don't know what's in production, what we're using for the house. So because it's difficult for them to categorize us, they just don't.&quot;</td>
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<td>the government doesn't know how to categorize us</td>
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<tr>
<td>Where do we find all of this information?</td>
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<tr>
<td>Not enough appropriate information is accessible</td>
<td>so much knowledge is lost</td>
<td>&quot;When they planted the coffee, they got rid of a lot of the Indigenous plants they were</td>
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<td></td>
<td>not too much people doing this</td>
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Systems for accessing land, capital, and markets favor short-term production and economic value

The first dimension of themes was that systems for accessing land, capital, and markets favor short-term production and economic value. Many practitioners echoed the theme that “it’s not easy to find those kinds of leases”. Agroforestry practitioners struggle to secure long-term tenure, due to high land prices and landowners only offering short-term leases.

Even with land access, agroforestry practitioners still face other economic obstacles, which fell into three themes. The first was having the start-up capital. The second was keeping up with maintenance and expenses while waiting for perennial plants to mature. For example, one practitioner described how windbreaks need to be established at least a year before planting cacao, and then the cacao takes three to four years to mature, “So, it's a good four-to-five-year window of nothing but negative cash flow”. Third, practitioners felt constrained by the pressure to turn a profit in the short term. While this pressure can motivate agroforestry transitions, for example when orchardists plant annual crops between their trees for short-term income, the practitioners we interviewed primarily chose agroforestry as an intentional system, not just for economic benefits, and thus saw this pressure primarily as a barrier. Because of pressure to turn a profit in the short term, the cacao farmer first planted cacao in monoculture, which left the the crop vulnerable to wind: “ironically, everything that led us to our first big mistake, that led us to where we finally are now, had to do with trying to run fast enough to make money.”

Two themes related to how practitioners try to circumvent economic obstacles. The first theme was “it’s hard to do education and production”. Some practitioners use agricultural production or education grants to augment cash flow. Yet, practitioners expressed that time spent on education programs takes away from time spent in the field, growing plants for harvest. Many
practitioners felt stuck relying on grants to cash flow their sites instead of becoming financially self-sustaining through production. Second, “being tied to fiscal year deliverables” limits practitioners’ ability to manage “when nature is ready for me to do it, as opposed to when the fiscal year requires me to do it”. Grants can be good for start-up, but without proper planning, it can be difficult to keep up with maintenance and cash flow until the perennials start to produce. One practitioner expressed, “one of the things that's really hard is whenever you get grants and things from nonprofits, it lasts a few years, and then you have to re-compete; to grow a forest, you need 100 years.”

Indigenous and local knowledge is not adequately valued

Second, many agroforestry practitioners fall through the cracks because of a lack of value for Indigenous and local knowledge. The most referenced theme was that local practitioner knowledge is not valued. For example, practitioners described how agroforestry definitions and recommendations center knowledge and experience from the continental U.S. One practitioner expressed this frustration about a funder, “their thing was they wanted us to be following American forestry practices, so, for example, planting koa on a 10 foot by 10 foot grid, and for us, and on our terrain, that's just not really realistic or practical and didn’t really make sense to us.”

Another example of how practitioners experienced the lack of value for local knowledge was through cultural appropriation. Agroforestry does not have one parallel Indigenous agroecosystem. Instead, it is a Western construct that is an umbrella term for a variety of place-based practices that integrate trees and other plants in various arrangements and intensities. For example, in Hawai‘i forms of agroforestry may be called pākukui (Lincoln, 2020), kaluʻulu (Menzies, 1920; Kelly, 1983; Quintus et al., 2019), or ka malu ʻulu o lele. One practitioner explained how using the term agroforestry can therefore exclude the participation of Indigenous people who are familiar with integrated forest-agriculture practices, but not the term agroforestry. Another expressed that labels like permaculture and agroforestry are “just whitewashing Hawaiian culture”. Many of the Kānaka ʻŌiwi practitioners we spoke with felt uncomfortable with the use of the term. One explained the source of their discomfort,
“And most of that has to do with the fact of our historical references show of this older style and technique and this exact thing [...] In the end, I still want to be able to find a term that can credit our works that we do to the people that are of the place, the other Indigenous organisms that had that same relationship and style and study that we’re all today putting scientific terminology labels on.”

Another related theme in this dimension was that agroforestry is generally framed as a technical practice. One permaculturalist commented, “Agroforestry is an excellent system, but it doesn't include those ethics.” A Kānaka ʻŌiwi practitioner explained that their stewardship system contains significant cultural knowledge, so “a lot of the difference between agroforestry and [our system] is just that, ‘culture’; And what we stress is no more agriculture without culture.”

Then, the theme “money is what talks” further illustrated the conflict in values constraining practitioners. A Kānaka ʻŌiwi practitioner said it had been challenging “in a world that's really driven by economics in numbers” to make initiatives like theirs fundable, because they “want to look at the social good of what they're doing”. A major challenge is the mis-match in metrics of success: “How do you measure our kupuna [elders] planting a tree with their moʻo [lineage], that feeling, that reciprocal exchange between environment, their relationship to the environment and us, kānaka [Hawaiians]?”. The extra work that local and Indigenous practitioners do to translate between value systems is a major constraint to equitable transitions. Another Kānaka ʻŌiwi practitioner described how in a new field that they had recently opened up, they had to choose between planting ipu (gourd; Lageneria siceraria), which has important cultural value for hula (dance) and food, or lilikoi (passion fruit; Passiflora edulis), which a company that makes value-added products for tourists already committed to buying. Although they are motivated to practice agroforestry as an act of resistance to capitalism, practitioners still struggle to achieve financial sustainability within the system.

**Institutions are siloed**

Finally, agroforestry practitioners fall through the cracks because their practices do not fit within the silos of regulatory, funding, and other support organizations, and of dominant worldviews that separate agriculture and forests. The first theme in this dimension was the
polarization between conservation and agriculture within government, private organizations, and social norms. One silvopasturist described this as an issue of “philosophy”, explaining, “I think one of the greatest challenges for both the livestock industry and for the conservation community is trying to find the middle ground that exists between the two; you know, we're polarized.”

The second theme was that “the government doesn’t know how to categorize us”. Because agroforestry crosses sectoral silos, government agencies and other organizations that remain siloed often struggle with how to categorize agroforestry practices, limiting practitioners’ access to support. For example, one practitioner described how they struggled to qualify for agricultural exemptions because the property tax office could not tell what part of the land was “in production” because the agroforestry practice did not look like an orchard. Another practitioner explained how they fail to qualify for federal farm benefits because they produce a native forest plant, which is not on the approved list of crops. They added another reason they struggle is because their approach is to restore the forest ecosystem around the plant: "that's one reason why we fall through the cracks, because we're not looking at it as we're producing one particular crop." Additionally, policymakers’ siloed conceptualizations of agriculture limit practitioners’ access:

“When you're talking to policymakers, and they have no idea what you're talking about, as far as agroforestry, it's very difficult to try and get them to attach to the idea that we need leases extended. You know, for them, it's just like, ‘Well, why don't you just go do farming the way everybody else does farming?’.”

Not enough appropriate information is accessible

The dimensions of agroforestry-specific structural obstacles produce a secondary dimension of challenges: not enough appropriate information is accessible (Table 4.2). The most referenced theme was “so much knowledge is lost”. Colonization, land dispossession, plantation agriculture, and ranching severely marginalized Indigenous agroforests and their stewards in Hawai’i. Many practitioners motivated to restore these systems explained how the lack of Indigenous and local knowledge was a major barrier to their ability to transition to agroforestry. While many practitioners are reclaiming this knowledge, practitioners expressed two additional themes of obstacles: “there's not too much people doing this” and “there's no place for the people with knowledge to share”. Further, practitioners expressed difficulty knowing what to
plant and that agroforestry is “so place specific”. Another theme was challenges related to how to balance diversity-efficiency trade-offs. For example, one practitioner acknowledged that “that’s why there’s monocrop; it makes everything easier.” Thus, practitioners are continuously experimenting to figure out, “how can we create an agroforestry system where we can still keep some of that principles, easy harvest and stuff, in place and still have a biodiverse system.”

Finally, a theme was “how do we scale up?” Many people have retained home garden practices, but figuring out how to practice on the scale of 5, 10, or 100 acres raises many questions.

**Access to external resources shapes who gets to practice agroforestry**

Practitioners rely on resources external to their site, especially financial and social capital that are unequally distributed, and a strong commitment to their values in order to participate in agroforestry transitions (Table 4.3). Reliance on external resources, especially financial capital, translates to new farmers on the whole in Hawai‘i being “older, wealthier, and less diverse than the general population” (Suryanata et al., 2021). Yet, we interviewed a higher Kānaka ‘Ōiwi population by percentage than the general population. This provides an opportunity to understand the resources, networks, and institutions that allow these practitioners and others to participate in agroforestry transitions. Here, we describe these factors as they relate to each dimension of agroforestry-specific obstacles.
Table 4.3. Factors influencing practitioners’ ability to participate in transitions to agroforestry in Hawai‘i related to each dimension of agroforestry-specific obstacles.

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<thead>
<tr>
<th>Dimension</th>
<th>Theme</th>
<th>Illustrative Quote</th>
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<tbody>
<tr>
<td><strong>We fall through the cracks</strong></td>
<td>can write grants</td>
<td>“You know, we're lucky. I think one of the benefits of working for a private enterprise like a ranch is that we can self-fund, and that’s really important. We have more control over the project and project timeline.”</td>
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<tr>
<td>Systems for accessing land, capital, and markets favor short-term production and economic value</td>
<td>can self-fund</td>
<td>“That's what helps to overcome that challenge is partnerships with our community members with other resources.”</td>
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<td></td>
<td>have people who kāko‘o (support)</td>
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<td></td>
<td>have partnerships</td>
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<td>have access to equipment</td>
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<td></td>
<td>can create new markets</td>
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<td></td>
<td>have cheap or volunteer labor</td>
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<td></td>
<td>someone else takes on the marketing</td>
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<td></td>
<td>bought land at the right time</td>
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<td></td>
<td>inherited land</td>
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<td></td>
<td>take on the risk of uncertain land tenure</td>
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<tr>
<td><strong>Indigenous and local knowledge is not adequately valued</strong></td>
<td>can act as translator between community and institutions</td>
<td>“The sugar companies inherited some of the most fertile, abundant lands in Hawai‘i, and they completely ruined it. But we don’t accept that. We can’t accept that in our generation to just say, they're ruined, and they're done. [....] And if we accept that, then it's done, we're done. And so, we said, no, we'll figure it out, we have to figure it out, otherwise, who is going to do it?”</td>
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<td>have the mindset ‘we don't just walk away’</td>
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<td>aloha ‘āina (love of the land) discourse</td>
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<tr>
<td><strong>Institutions are siloed</strong></td>
<td>can self-fund</td>
<td>“So over the last 20 years, it's almost like 20 years and a month, we've been working with Farm Service to establish ourselves as a legitimate farm producing a product.”</td>
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<td></td>
<td>can act as self-advocate, translator, and educator</td>
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<td><strong>Where do we find all of this information?</strong></td>
<td>experienced traditional agroforestry first hand</td>
<td>“I have to say that that kind of diverse farm is not possible without having the diverse background that I had, right? Most people would not be able to do that, because they don't have the resources at hand with people around the world that, you know, we traded seeds, we traded information, we traded knowledge. [...] These are resources that were there, not for the taking, but were available to certain people.”</td>
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<tr>
<td>Not enough appropriate information is accessible</td>
<td>have a mentor</td>
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<td></td>
<td>have access to ‘ike kupuna (ancestral knowledge)</td>
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<td>have a practitioner network</td>
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<td></td>
<td>create your own opportunities</td>
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<td></td>
<td>existing books and information resonate</td>
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<tr>
<td></td>
<td>ma ka hana ka ‘ike (learn through doing)</td>
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Systems for accessing land, capital, and markets favor short-term production and economic value

Four themes arose as factors broadly influencing access to land, capital, and markets. First, nearly a third of practitioners cited their ability to write grants as an advantage. Eighty percent of practitioners we interviewed had attended at least some college, and almost half of those practitioners had graduate degrees. The skills gained through academic education helped people access financial resources: “we were lucky because of our professional background, that we can write grants [...] that’s a disadvantage that other farmers have.” Yet, access to academic education is unequally distributed. Further, grants are often tied to educational programming deliverables, which align with values-based reasons for choosing agroforestry, yet reproduce obstacles such as taking time away from production and being tied to fiscal year deliverables. This theme also included other forms of financial assistance like incentives and cost-share programs. Yet, again, accessing these funds required extra time, knowledge, and persistence to learn the rules and figure out how to leverage the funds to support their vision of agroforestry. Although grant funds have allowed many people to begin to transition to agroforestry, there was a sense that the burden of administration was unsustainable, and the amount of time left to actually tend their agroforestry systems was insufficient.

Second, the ability to self-fund influenced who could participate. This looked different in each case. Some practitioners held a full time off-farm job, had a spouse with a full time off-farm job, used retirement funds or other personal savings, or used a cash inheritance. Next, many people spoke to the value of two interrelated themes: having people who kākoʻo (support) and having partnerships. People who kākoʻo share their time, skills, equipment, and other resources in support of the practitioner transitioning to agroforestry. Similarly, partnerships and collaborations between sites, organizations, and/or institutions provided access to resources. For example, six practitioners either engaged other partners to help purchase land or partnered with wealthier individuals who already owned land, often through employment. Although in these cases practitioners have long-term tenure, this comes with a trade-off of decision-making power. As one practitioner said of other Kānaka ʻŌiwi in their position, “A bunch of us got people watchin’ over our shoulders”.

Three themes emerged around land access specifically. First, was that practitioners “bought the land at the right time”, often referring to when land was less expensive after the
sugar plantations closed. This was the case for some of the eight practitioners who owned land as a single ʻohana (family) unit and said they would not have had the means to self-fund today. Another theme was inheriting land as a group of descendants. In these four cases, shared decision-making challenges and pressure to sell by some co-owners challenged secure land tenure. A third theme specific to land access was taking on the risk of uncertain tenure. Nearly one third of sites leased the land that they steward, and of those, only a few had leases longer than a few years, including three commercial cacao enterprises with 30-year leases. Short term leases can carry a significant burden of risk. For example, one practitioner described how they recently lost access to the land they had been transitioning to agroforestry: “we're just now getting to the point where this piece of land is giving us the most special fruits that we've been waiting years on, and now we have to leave that land.”

Finally, two themes related to market access. First, practitioners expressed that their ability to create new markets has helped them persist. For example, one grower explained how they created markets for dye plants and lei flowers by building relationships with cultural practitioners. The second theme was having someone else take on the marketing. For example, a māmaki grower explained that “those kinds of regulations is on them [the buyer], the value added processing part, they’re taking it on” and as a result, practitioners can just grow, harvest, and sell the wet māmaki. She added, “it's such a joy”. Having an intermediate buyer who handles distribution and marketing to consumers is key and well established for ʻulu (breadfruit; Artocarpus altilis), māmaki (Pipturus albidus), and ‘awa (kava; Piper methysticum) on Hawai‘i Island. But this is still a major obstacle for most other crops.

**Indigenous and local knowledge is not adequately valued**

The ways practitioners deal with the lack of value for Indigenous and local knowledge fell into three themes. First, practitioners expressed the theme that they persist by being able to act as a translator between community and institutions, such as policymakers, funders, and government agencies. The extra unpaid work is disproportionately required of Indigenous practitioners and takes them away from production. This means Indigenous practitioners get behind non-Indigenous practitioners in agricultural skill development and production. One Kānaka ‘Ōiwi practitioner expressed that, “We're lucky because, brah, Hawaiians is very resilient. And we can adapt, and we figured out how to communicate […], but it's so exhausting...”
The second theme was that practitioners have the mindset “we don't just walk away”. Despite their success in transitioning to agroforestry hinging on their ability to dedicate extra unpaid time, practitioners expressed their feeling of responsibility to persist. For Kānaka Ōiwi practitioners especially, this responsibility and persistence is interlinked with their motivations to restore relationships with ʻāina, ancestors, and culture.

Finally, practitioners’ strength also comes from aligning their work with aloha ʻāina discourse and the Hawaiian sovereignty movement. Aloha ʻāina is a discourse and set of practices that organizes and engages a diverse Kānaka Ōiwi community for political action (Trask 1987; Baker, 2021). This discourse is enacted through other forms of Indigenous agroecosystems such as lo‘i kalo (wetland taro; *Colocasia esculenta*) and loko iʻa (fishponds). However, in the case of lo‘i kalo, for example, there is a clear vision of what these systems are and how they are both a form of cultural revitalization and food production. Since agroforestry does not have a single parallel Indigenous land use practice, and so much of the knowledge is lost on how Indigenous agroforestry systems were managed to be a significant form of food production, practitioners still struggle to persist despite the support from aloha ʻāina discourse.

**Institutions are siloed**

Two themes emerged illustrating who is able to transition to agroforestry despite siloed institutions. First, practitioners who can self-fund are able to transition. This included practitioners with the financial resources to persist without the support of tax exemptions, cost-share incentives, grants, and other funding. The second theme was practitioners who can act as a self-advocate, translator, and/or educator. In these cases, practitioners took extra time to translate their motivations and practices into the current production-focused system and educate institutions about how their practices fit. This is similar to how practitioners deal with the lack of value for Indigenous and local knowledge. One practitioner stressed that rather than reaching out for support from government agencies, they are now taking the approach of just “doing it on our own”. The few strategies that practitioners use to circumvent this dimension of falling through the cracks - the ability to self-fund and extra time - has an exclusionary effect on practitioners who lack the resources to go at it alone.
Not enough appropriate information is accessible

Several themes arose surrounding practitioners’ ability to circumvent the lack of accessible appropriate information. First, nearly a third of practitioners had experienced traditional agroforestry, mostly through visiting other Pacific Islands like Fiji, Tonga, Samoa, Micronesia, and the Philippines – either on self-funded trips or for an off-site job. Seeing other agroforestry systems provided “good inspiration” and a way to gain “first-hand knowledge”, yet requires significant time and funds to do so. Second, almost a third of practitioners identified the theme that having a mentor helped them. Then, for practitioners trying to build from Kānaka ʻŌiwi models of agroforestry, many went through a process of “triangulating knowledge” since no complete information source is available. Practitioners described combining information from different sources including those falling into the themes of experiencing traditional agroforestry first-hand, accessing ‘ike kupuna (ancestral knowledge), having a practitioner network, and ma ka hana ka ‘ike (learning through doing). Practitioners accessed ‘ike kupuna through archival research or, in only a few cases, from family members. Although historical records are a valuable source of information, it can take significant time to find and translate from ‘Ōlelo Hawai‘i (Native Hawaiian language), which practitioners are not compensated for, although some conducted this research as a part of an academic degree program to circumvent this obstacle. Similarly, another theme was that practitioners persisted in part because of their ability to create their own opportunities to learn. Finally, some practitioners also identified that existing permaculture and agroforestry resources helped them, pointing to how this information resonates with some people.

DISCUSSION

We interviewed agroforestry practitioners in Hawai‘i to understand motivations for, and obstacles to, agroforestry transitions and the factors that influence who is able to participate in these transitions. We found that most transitions occurred when practitioners gained new access to land, due in part to the historical context of land dispossession and accumulation by non-Hawaiians and colonialism. Most practitioners we interviewed chose agroforestry intentionally for non-economic, values-based reasons, with direct or practical benefits as secondary reasons. Practitioners’ values and resulting practices, based in relationships and reciprocity, conflict with dominant institutions’ values, which prioritize short-term production and economic profit. These
contested values and an imbalance in power between practitioners and landowners, government agencies, policymakers, and other institutions cause agroforestry practitioners to fall through the cracks. To participate in agroforestry transitions, practitioners rely on resources external to their site, especially financial and social capital that are inequitably distributed, and a strong commitment to their values. Figure 4.3 illustrates these major findings and emphasizes the social and ecological potential of removing constraints to agroforestry regeneration. Our case study highlights three interrelated key points with important implications for realizing just agroforestry transitions: 1) practitioners transition to agroforestry to restore ecosystems and reclaim sovereignty, not just for the direct benefits; 2) a major constraint to agroforestry transitions is that the term agroforestry is both unifying and exclusionary; 3) structural change is needed for agroforestry transitions to be just.
Figure 4.3. Practitioners’ values and resulting agroforestry practices, based in relationships and reciprocity, conflict with dominant institutions and systems of resource access in Hawai‘i that value short-term production and economic profit. These contested values and an imbalance in power between practitioners and landowners, government agencies, policymakers, and other institutions cause agroforestry practitioners to fall through the cracks. This illustration depicts how the conflict of values and power is like a tree whose top has been cut off and a new top grafted on, but the two trees (value systems) are incompatible, so the grafted tree struggles to survive and never produces fruit. Many Indigenous and local practices of agroforestry (area below the graft wound) are rooted in ancestral knowledge (roots and reflection below ground)
and are impeded by the values of the dominant regime (grafted top). Some Indigenous and local practitioners are able to circumvent obstacles (push past the graft wound), yet structural change is needed to create more equitable access to participation and enable more just agroforestry transitions. Artwork by Tehina Kahikina.

**Practitioners transition to agroforestry to restore ecosystems and reclaim sovereignty**

Our results highlight how practitioners are motivated to transition to agroforestry by their values, not just the direct or practical benefits of agroforestry. In this way, for many of the practitioners we spoke with, both Indigenous and non-Indigenous, transitioning to agroforestry was a political act through which practitioners sought to reverse social and ecological damage. Practitioners chose agroforestry purposefully as a form of ecological or biocultural restoration (Kimmerer, 2011). The values many practitioners held aligned with new agrarianism articulated in other diversified agriculture transitions (Mostafanezhad and Suryanata, 2018). Importantly, our case study also highlights a population of agroforestry practitioners motivated to reclaim Indigenous agroecosystems and food and cultural sovereignty, an aspect of agroforestry transitions that is often overlooked in the adoption literature (although see Dove, 1990). This points to the need for agroforestry research to more explicitly examine how social movements engage with agroforestry transitions, which is more common in agroecology research (Gliessman, 2016). Our findings thus reaffirm the importance of applying political ecology (Robbins et al., 2015; Robbins, 2019) and political agroecology (Molina, 2013) approaches to the study of agroforestry transitions. Given that our initial list of agroforestry practitioners included a significant number of Kānaka ʻŌiwi organizations and practitioners, this might have translated to a higher representation of these groups as study participants than the population of agroforestry practitioners as a whole in Hawaiʻi. Yet, this should not downplay the importance of their voices. Instead, our findings highlight the need to revise how agroforestry is framed in outreach, policy, and programs to be more inclusive of people trying to restore and adapt historical Indigenous agroforestry systems, rather than simply transition to agroforestry as a means to achieve production and economic benefits. Combining power sensitive and feminist approaches could further illuminate how not only capitalism and colonialism, but also heteropatriarchy affect these transitions (Espinal et al., 2021). Future research could explore the
extent to which the Pacific Islander diaspora in Hawai‘i engages in Indigenous agroforestry practices and what obstacles to participation they face. Future studies could also investigate what other actors - land owners, existing farmers and land managers who do not practice agroforestry, and other people interested in transitioning - perceive as drivers and or constraints to agroforestry transitions.

The term agroforestry is both unifying and exclusionary

The unique motivators that emerged from our interviews create obstacles that do not exist for other types of agriculture, and that are not widely recognized. Importantly, one overarching constraint is the contradiction arising from how the term agroforestry is framed and used. Institutions like philanthropic organizations and federal and state government agencies who have the power to set resilience agendas often frame agroforestry as a multi-benefit land use linking agriculture and forest conservation (Ollinaho and Kröger, 2021). Practitioners use this frame to align their initiatives with funder priorities, making “agroforestry” a gateway to accessing resources. However, as illustrated in our interviews, the cultural norms and policies of these same institutions are still largely siloed and favor short-term production and economic value, which constrain agroforestry practitioners. Agroforestry in principle belongs to all sectors, but in practice, it belongs to none (Buttoud, 2013). This contradiction challenges inclusive participation in agroforestry. Further, many interviewees viewed the term agroforestry as a form of cultural appropriation, which can add to its exclusivity. To move beyond this contradiction requires desiloeing institutions and allowing for plurality in framing. One way to start is to increase communication, cooperation, and coordination between agriculture, forestry, conservation, and cultural organizations that support land stewards. Acknowledging and using culturally appropriate names for agroforestry locally is another incremental step. Future research could examine existing agriculture and forestry policies at local, state, and national levels and consider how their framing may drive or constrain inclusive agroforestry transitions and what changes are needed.

Structural change is needed for agroforestry transitions to be just

This case study illuminated that without the means to self-fund, practitioners’ ability to start practicing agroforestry and persist through the transition process is tenuous. The continuous struggle over values and imbalance in power between practitioners and institutions constrains the
ability for agroforestry transitions to be just. We emphasize that structural change is needed to address these issues. Some changes may support all diversified agriculture since agroforestry practitioners share many obstacles with other producers. Yet, some solutions are unique because agroforestry practitioners' motivations and practices are different. Practitioners we interviewed emphasized the need to create more relationships, partnerships, and collaborations to increase inclusive participation in agroforestry. This reinforces other findings that transformations require not just changes in land use practices, or the adoption of technological practices, but the re-thinking of social relations and structures (Galt, 2013). And, while the practitioners we spoke with are working locally to transform the dominant agricultural system, additional support from institutions is needed to ensure local level domains of transformation can affect broader regime change (Anderson et al., 2019).

**Restore long-term land access that empowers Indigenous practitioners**

Our results highlighted that secure, long-term land access is a major constraint to agroforestry. Therefore, solutions are needed to increase the duration of leases and other access agreements, increase Indigenous practitioners’ access to these tenure arrangements, and empower practitioners with decision-making autonomy. Opening up land access, especially under longer tenure agreements, needs to focus on restoring Kānaka ʻŌiwi access to ensure just outcomes. As one practitioner questioned, “if we open up trust lands to everybody, what protects Kānaka ʻŌiwi interest?” and expressed his concern directly, “we keep losing as Hawaiians and other people keep benefiting”. Future research needs to examine how potential interventions to improve land access for agroforestry practitioners will affect Kānaka ʻŌiwi. We found that in Hawai‘i, private and public policies meant to protect landowners from risk and/or agricultural land from mismanagement, such as short-term leases and policies against living on agricultural land, put a higher burden of risk on tenants, especially those practicing agroforestry. Although the leases of many practitioners are bolstered by public discourse around the value of farming (Mostafanezhad and Suryanata, 2018), short-term leases still place a significant burden on practitioners to continually prove their worth relative to other land uses, like development. Tenants hold little power to negotiate lease arrangements, and therefore participation in stewardship practices like agroforestry is constrained.
Re-value Indigenous and local knowledge

Our findings also underscore how the lack of value placed on Indigenous and local knowledge is a major constraint to agroforestry transitions. Therefore, one strategy to enable more equitable agroforestry transitions is to re-honor the role of farmers as not only feeders, but also land and water protectors and public health stewards. Colonialism, and the low value placed on labor in plantations, de-valued the important role that mahiʻai (farmers) played in the Hawaiian Kingdom and have contributed to an enduring process of erasure (Peralto, 2013). Interviewees described how this legacy and the physical struggles of farm labor feed the stigma that farming is a less desirable job than higher paying, less physically strenuous jobs, which constrains the re-generation of agroforestry today. As such, (re)honoring farmer livelihoods, lifestyles, and knowledge is critical to restoring Indigenous crops (Kagawa-Viviani et al., 2018), the foundation of many agroforestry systems. In turn, developing metrics for the contributions agroforestry practitioners make to their communities and society is another way to re-value their role. Future research could include co-developing biocultural indicators (Dacks et al., 2019) with agroforestry practitioners to honor place-based metrics of success. Although bringing attention to the societal benefits is important, it is critical not to downplay the cost of producing these benefits, so as not to undervalue farm work, which can normalize self-exploitation and lead to burnout (Suryanata et al., 2021).

Rebuild resilient support infrastructure for agroforestry practitioners

Our results highlighted the importance of developing stronger infrastructure to support practitioners so that they can focus on stewardship. This reinforces other findings that increasing resilience of agricultural production systems requires supporting farmers as individuals so that they can grow food (Rissing et al., 2021). For example, practitioners we spoke with pointed to the need to better align investment capital with agroforestry initiatives. Additionally, practitioners expressed the need for support to get their products into markets including processing and distribution infrastructure, as well as buyers and consumer demand. This is a common constraint with agroforestry in other contexts because agroforestry products often lack existing markets and one practitioner may produce multiple products with lower volumes of each (Amare and Darr, 2020; Sollen-Norrlin et al., 2020). Additionally, there is a need to value not only capitalist markets, but also other modes of alternative market and non-market forms of
exchange. Creating standards for agroforestry products may assist with marketing (Elevitch et al., 2018), although more research on the power dynamics and who benefits from these initiatives is needed to ensure equitable outcomes (Anderson et al., 2019). Structured demand or mediated markets are also a possible alternative (Guerra et al., 2017; Valencia et al., 2019).

Finally, our results emphasized the need to support practitioners in accessing place-based information and learning from each other, rather than knowledge deficit interventions that overlook structural barriers (Calo, 2018). Creating practitioner networks, particularly for Indigenous practitioners would be a key first step. In Hawai‘i, similar networks already exist for limu (seaweed) gatherers (The Limu Hui), loko i‘a (fishpond) practitioners (Hu‘i Mālama Loko I‘a), and taro growers on Kaua‘i (Waiʻoli Taro Hui), providing possible templates for agroforestry practitioners. Additionally, compiling place-based land use history into readily accessible formats for practitioners, following a historical restoration approach (Kurashima et al., 2017), could lower the burden to transitioning. Finally, increasing funding for research on place-based diversified farming systems could increase structural support for agroforestry transitions (Carlisle and Miles, 2013) and disrupt the lock-in of economic and policy forces that incentivize low diversity cropping systems (Mortensen and Smith, 2020). Future research could analyze social networks to identify further leverage points for change.

CONCLUSION

Agroforestry is widely promoted as a resilient land use. Yet, contested values and unequal power dynamics between practitioners and dominant institutions constrain just transitions to agroforestry. Our case study illuminates three interrelated key points that have important implications for realizing resilient and just agroforestry transitions. First, we find that agroforestry is intentionally chosen as a form of restoration and reclamation of sovereignty, not only as a means to production and economic benefits. Second, agroforestry faces an important contradiction: the same institutions that promote agroforestry also perpetuate the dominant systems of resource access, values, and silos that constrain agroforestry practitioners. Third, structural change is needed to enable just and lasting participation in agroforestry transitions. This work reinforces the need to consider the politics and power dynamics in agroforestry transitions and points to numerous future directions for participatory, action-oriented research.
ACKNOWLEDGMENTS

We thank all of the practitioners who entrusted us with their knowledge and without whom this study would not have been possible. We are grateful to Tehina Kahikina for collaborating on the artwork for Figure 4.3. We also thank one anonymous practitioner for sharing the grafted tree metaphor that helped inspire Figure 4.3. We are grateful to Krisna Suryanata for contributing to study development and for valuable suggestions on earlier drafts of the manuscript. We also thank Leah Bremer for feedback during study development and on an earlier draft.
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Swanson, D. (2016). The number of Native Hawaiians and part-Hawaiians in Hawai‘i, 1778 to 1900: Demographic estimates by age, with discussion. in.


APPENDIX 4.1

DATE: February 04, 2020
TO: Ticktin, Tamara, PhD, University of Hawaii at Manoa, Botany Wong, Male, Windward Community College, Natural Science, Hoppe, Tressa, University of Hawaii at Manoa, Botany, Hastings, Zoe, University of Hawaii at Manoa, Botany
FROM: Rivera, Victoria, Dir, Ofc of Risch Compliance, Social&Behav Exempt
PROTOCOL TITLE: Survey of agroforestry in Hawaii
FUNDING SOURCE: USDA National Agroforestry Center Agroforestry Outreach RFP, NSF Graduate Research Fellowship, University of Hawaii Sea Grant College Program
PROTOCOL NUMBER: 2019-00905
APPROVAL DATE: February 04, 2020

NOTICE OF APPROVAL FOR HUMAN RESEARCH

This letter is your record of the Human Studies Program approval of this study as exempt.

On February 04, 2020, the University of Hawaii (UH) Human Studies Program approved the study as exempt from federal regulations pertaining to the protection of human research participants. The authority for the exemption applicable to your study is documented in the Code of Federal Regulations at 45 CFR 46.101(b)(2).

Exempt studies are subject to the ethical principles articulated in The Belmont Report, found at the OHRP Website www.hhs.gov/ohrp/humansubjectsguidance/belmont.html.

Exempt studies do not require regular continuing review by the Human Studies Program. However, if you propose to modify your study, you must receive approval from the Human Studies Program prior to implementing any changes. You can submit your proposed changes via the UH eProtocol application. The Human Studies Program may review the exempt status at that time and request an application for approval as non-exempt research.

In order to protect the confidentiality of research participants, we encourage you to destroy private information which can be linked to the identities of individuals as soon as it is reasonably to do so. Signed consent forms, as applicable to your study, should be maintained for at least the duration of your project.

The approval does not expire. However, please notify the Human Studies Program when your study is complete. Upon notification, we will close our files pertaining to your study.

If you have any questions relating to the protection of human research participants, please contact the Human Studies Program by phone at 808-548-607 or email uhhrb@hawaii.edu. We wish you success in carrying out your research project.
## APPENDIX 4.2

Semi-structured interview guide

<table>
<thead>
<tr>
<th>Section</th>
<th>Questions</th>
<th>Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introductions and consent form (5 min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How is agroforestry occurring in Hawai‘i today? (15 min)</td>
<td>1. (How did you get here?) What led you to farm/steward this way in this place?</td>
<td>how long have you lived in Hawai‘i, farmed in any place / in this ʻāina/place, how would you describe your relationship with this ʻāina/place, land tenure</td>
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<tr>
<td></td>
<td>2. How did [this agroforestry system] come to be here? (Can you tell us the story of how this agroforestry system came to be here?)</td>
<td>always practiced this system/ inherited it from someone, practiced conventional system and added trees, started with secondary forest and selectively thinned, land use history</td>
</tr>
<tr>
<td></td>
<td>a. Who was involved in transitioning to this land use from the previous use?</td>
<td>‘ohana, friends, other farmers, NGO, foundation, extension, consultant, researcher</td>
</tr>
<tr>
<td></td>
<td>b. What activities, costs, information, and support were involved?</td>
<td>Info: enterprise budgets, species/crop data, land use history, TEK/ILK Costs: clearing, planting material, fencing, irrigation Support: forester/extension/outside staff helped with planning; grants, EQUIP payment or other cost-share; DOFAW Forest Stewardship Program</td>
</tr>
<tr>
<td></td>
<td>3. What is the system like now?</td>
<td><strong>size</strong> Since we can't be there in person with you, can you paint a picture for us?</td>
</tr>
<tr>
<td></td>
<td>a. What plants/animals are there?</td>
<td>annual crops/plants (e.g., tomato, cucumber, sunflower); perennial, non-tree crops/plants (e.g., kalo, ʻuala, mamaki, orchid); tree crops (e.g. mango, papaya, breadfruit, coffee, macadamia nuts); timber; animals/livestock (e.g., sheep, cattle, chickens); bees (honey); native plants?</td>
</tr>
<tr>
<td></td>
<td>b. How are they integrated?</td>
<td>within field (intercropping, alley cropping, silvopasture), patches, on field margins (windbreak, fence), crop rotations (time), planting in forest understory</td>
</tr>
<tr>
<td>Question</td>
<td>Answer</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>c. Who is involved in the stewardship of this forest?</td>
<td>‘ohana, staff, volunteers, how many?</td>
<td></td>
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<tr>
<td>d. Who is involved in decisions about how to steward this forest?</td>
<td></td>
<td></td>
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<tr>
<td>e. What do you call this type of farming/stewardship system (if anything)?</td>
<td>kalu‘ulu (very specific term for ulu cultivation system of Kona), pākukui, paia hala, mahi la'a, indigenous agriculture/farming, agroforestry, silvopasture, alley cropping, forest farming, food forest, wind break, riparian buffer, living fence</td>
<td></td>
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<tr>
<td>What factors drive and/or restrain practitioners’ decisions to practice agroforestry?</td>
<td>What motivates you to steward this type of system? Are there specific benefits you receive or anticipate receiving from this system? How do you define the success of this system?, biocultural restoration, incentive payment, neighbor, perpetuation of traditional and customary practice, ability, willingness, social, and governance metrics</td>
<td></td>
</tr>
<tr>
<td>(15 min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Why do you integrate trees and crops (or other plants/animals) together instead of growing only trees or only crops or growing them separately?</td>
<td>access to land (annual lease, high rental cost, lease negotiation timeline, inefficient consent of entry/permitting processes), labor, capital, loss of ILK/TEK, weeds, institutional/structural/governance, availability of planting material</td>
<td></td>
</tr>
<tr>
<td>5. What challenges/barriers have you faced in stewarding this forest?</td>
<td>farmer capacity development (agroforestry hui, training, extension, info provision, demo sites, participatory trials, business planning, system design); access to germplasm (provision or facilitation of access to seedlings/seeds); community-level advocacy (planting events); incentive provision (direct payments for planting/tending trees, premiums for crops, carbon payments (PES), other access to capital/loans); market linkage facilitation/access (access to distributor, forward contract); policy and institutional change (ability to live on land, change in rules, change in taxes, change in qualifications for incentive program, etc.) (Miller et al. 2020)</td>
<td></td>
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<tr>
<td>How can a better understanding of the above inform structural changes that enable the equitable scaling of agroforestry systems?</td>
<td></td>
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<tr>
<td>(10 min)</td>
<td></td>
<td></td>
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<tr>
<td>6. What would help you overcome these current challenges?</td>
<td></td>
<td></td>
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<tr>
<td>7. Have you noticed changes to the ʻāina you farm/steward/access since you started this system?</td>
<td>when we talked about motivations for this practice you mentioned [x benefit] – have you noticed a change in this since you started the system?,</td>
<td></td>
</tr>
<tr>
<td>9. What do you think would help more practitioners to steward land using integrated practices like the ones you use?</td>
<td>Are you familiar with conservation incentive programs like the DOFAW Forest Stewardship Program or NRCS EQUIP?</td>
<td></td>
</tr>
</tbody>
</table>
changes in soil, water, birds, insects, yields, plants, number of people interacting, biocultural indicators of success

8. What are your future hopes and/or plans for the ‘āina you steward/farm?

expand the area of this system, add/remove plants/animals, increase benefits that come from system (e.g., presence of native birds/plants, ecosystem services, crop yields, soil health, social/cultural), increase community engagement

10. Have the events since March 2020 (e.g., COVID-19) affected the integrated system you tend?

Do you anticipate changing your stewardship of this system and/or the amount of land you dedicate to this system due to these events?

<table>
<thead>
<tr>
<th>Individual Characteristics (2 min)</th>
<th>What is your highest level of formal education?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>What is your gender identity?</td>
</tr>
<tr>
<td></td>
<td>What is your age?</td>
</tr>
<tr>
<td></td>
<td>What race/ethnicity do you identify as?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Closing (2 min)</th>
<th>11. In what format would you like the results of this study?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>summary infographic/handout, webinar, presentation at farmer association meeting</td>
</tr>
<tr>
<td></td>
<td>12. Do you know of any other practitioners who tend systems that integrate trees and crops (or other harvested plants/animals)?</td>
</tr>
<tr>
<td></td>
<td>[probe: list of names] Would you recommend one for us to interview?</td>
</tr>
</tbody>
</table>

Thank you so much for your time. Those are all the questions we have for you. Do you have any questions for us?

We would like to send you a gift box as a mahalo for your time. What address would you like us to send it to?
CHAPTER 5. CONCLUSION

SYNTHESIS OF FINDINGS

Three main findings emerge from this dissertation: 1) applying two well established research approaches – co-production of knowledge and functional trait-based design – to agroforestry research can help produce more inclusive and scalable results (Chapter 2); 2) two agroforestry species mixes designed with this approach have similar effects on restoration outcomes in the first two years of establishment (Chapter 3); and 3) agroforestry practitioners are motivated to restore ecosystems and reclaim sovereignty, not just by practical benefits, but key structural obstacles limit who can participate in agroforestry transitions (Chapter 4).

The site-level study presented in Chapters 2 and 3 demonstrates a community-based approach to agroforestry research design and implementation. Analysis of plant community metrics over the first two years of restoration showed no difference between two agroforestry treatments, but did reveal a change in community composition from the pre-restoration ecological condition. Over the course of this site-level study, management questions beyond the initial design and planting arose. For example, uncertainty about how to deal with weed pressure, what type and how much irrigation to use, and the scalability of the management approach led to questions about who else is practicing agroforestry in Hawaiʻi today, what their systems and practices are like, and what their challenges are.

These questions became the impetus for the state-wide study conducted in Chapter 4, which draws on political ecology approaches to understand the multi-scalar drivers of, and barriers to, transitioning to agroforestry. We found that practitioners primarily chose agroforestry intentionally for non-economic and values-based reasons, rather than as a means to production or economic goals. Agroforestry practitioners face a similar suite of structural obstacles as other agricultural producers, including access to land, labor, and capital and ecological obstacles like invasive species and climate change. However, the conflict in values between practitioners and dominant institutions manifests as four additional dimensions of obstacles constraining agroforestry transitions: systems for accessing land, capital, and markets favor short-term production and economic value; Indigenous and local knowledge is not adequately valued; regulatory, funding, and other support institutions are siloed; and not enough appropriate information is accessible. Who is able to practice despite these obstacles is tightly linked with
people’s ability to access off-site resources that are inequitably distributed. Our case study highlights three key points with important implications for realizing just agroforestry transitions: 1) practitioners transition to agroforestry to restore ecosystems and reclaim sovereignty, not just for the direct benefits; 2) a major constraint to agroforestry transitions is that the term agroforestry is both unifying and exclusionary; 3) structural change is needed for agroforestry transitions to be just.

MANAGEMENT RECOMMENDATIONS

The results of Chapters 2 and 3 have several important implications for management. First is that regardless of the agroforestry species mix used for restoration, establishing high understory cover of agroforestry species from the start should be a management priority. This may require initially planting less desirable non-native, but non-invasive, species that are better adapted to compete with invasive weed species, which can dominate successional pathways in Pacific Island ecosystems. Relatedly, our results suggest that including some species that have traits associated with early successional environments (e.g., low stem density, small leaf area) in an agroforestry mix can improve restoration success. Finally, our results show that fallow agricultural lands dominated by non-native species hold high potential to be transformed into systems that have higher biodiversity and produce desirable products for the future. Increasing access to fallow agricultural lands and resources for their restoration through agroforestry should be a management priority.

Valuable management recommendations also emerge from Chapter 4. First, to address land tenure constraints, solutions are needed to increase the duration of leases and other access agreements, increase Indigenous practitioners’ access to these tenure arrangements, and empower practitioners with decision-making autonomy. Second is the need to revise how agroforestry is framed in outreach, policy, and programs to be more inclusive of people trying to restore and adapt historical Indigenous agroforestry systems, rather than simply transition to agroforestry as a means to achieve production and economic benefits. Creating space for plurality in what agroforestry means and looks like rather than promoting certain species and formulaic layouts would allow for more equitable participation in agroforestry transitions. Acknowledging and using culturally appropriate names for agroforestry locally is another important step. Relatedly, there is also a need to de-silo institutions. Although this is a large task,
one way to start is to increase communication, cooperation, and coordination between agriculture, forestry, conservation, and cultural organizations that support land stewards using agroforestry practices.

Next, our results highlighted the importance of developing stronger infrastructure to support practitioners so that they can focus on stewardship. For example, practitioners we spoke with pointed to the need to better align investment capital with agroforestry initiatives. Additionally, practitioners expressed the need for support to get their products into markets including processing and distribution infrastructure, as well as buyers and consumer demand. Finally, our results emphasized the need to support practitioners in accessing place-based information and learning from each other, rather than knowledge deficit interventions that overlook structural barriers. Creating agroforestry practitioner networks, particularly for Indigenous practitioners, would be a key first step.

LIMITATIONS

Like with any study, some limitations should be considered when interpreting the findings of this dissertation. First, while the size of the research site in Chapter 3 was most appropriate for the management context, a larger field site could have allowed us to increase the size and number of plots, increasing the statistical power to detect drivers of understory cover of agroforestry species and perhaps illuminating treatment effects that went undetected in this study. Next, high mortality of the species that were included in both treatments, likely due to transplant shock and unsuitable environmental conditions, limited our ability to answer an important initial question, of particular interest to Kākoʻo ʻŌiwi: with which agroforestry species mix do four culturally important plants in high demand have the highest survival? This could have been addressed by replanting the culturally important species in both treatments, and possibly additional facilitative species, if there had been sufficient funds. Additionally, as agroforestry systems take a long time to develop, a longer field study could have allowed us to better capture differences in restoration outcomes over the long-term.

In the state-wide study in Chapter 4, COVID-19 restrictions did not permit site visits. This likely limited the ability to understand the ecological characteristics of how agroforestry is occurring across Hawaiʻi. Although we reached saturation in themes, it is likely that the study missed some groups of agroforestry practitioners, such as Pacific Islanders practicing primarily
for subsistence and commercial agricultural producers who may incorporate trees primarily for
direct or practical benefits, for example fruit and nut tree growers using other trees for
windbreaks.

**OPPORTUNITIES FOR FUTURE RESEARCH**

This dissertation points to numerous future directions for participatory, action-oriented
research. First, at the site level, many gaps remain in our understanding of community dynamics
within agroforestry systems. While embedding a functional-trait approach to agroforestry and
restoration research design in a co-production framework can improve trait data availability by
incorporating data from Indigenous and local knowledge, significant gaps in trait data still exist.
More trait data is needed for native and locally important plant species, especially root traits, to
better understand biodiversity, ecosystem function, and ecosystem service relationships within
locally-appropriate agroforestry systems. Trait data for these species is also useful for designing
agroecosystems that are resilient to future socio-environmental change. Additionally, studies
could investigate strategies for using existing non-native species as a tool for biocultural
restoration, for example through connecting immigrant communities who have traditional
knowledge of the non-native plants with restoration sites, learning the cultural uses of plants in
their native ecosystems, and developing culturally appropriate value chains for non-native
species.

There are also many important research directions at the landscape and regional scale that
could build on this dissertation. For example, one gap is investigating what other actors - land
owners, existing farmers and land managers who do not practice agroforestry, other people
interested in transitioning to agroforestry, and support organizations and agencies - perceive as
drivers and/or constraints to agroforestry transitions. Also, exploring the extent to which the
Pacific Islander diaspora in Hawai‘i engages in Indigenous agroforestry practices and what
obstacles to participation they face is important. Future research could examine existing
agriculture and forestry policies at local, state, and national levels and consider how they may
drive or constrain inclusive agroforestry transitions and identify leverage points for change.
More equitable models of land access are critical to agroforestry transitions, which will require a
better understanding of how potential interventions to improve land access for agroforestry
practitioners will affect Indigenous communities. Co-developing biocultural indicators with
agroforestry practitioners could help honor place-based metrics of success. Future research could also analyze social networks to identify further leverage points for change. Finally, while most of the practitioners I interviewed cited non-economic motivations as the primary drivers of their work, they also expressed the challenge of having to operate within the existing economic system. Economic modeling, market analyses, and feasibility studies could help practitioners operate within current economic realities.

Overall, understanding what the potential is of restoring agricultural lands using agroforestry, and who is able to participate in agroforestry transitions, is critical to designing place-based interventions that lead to meaningful and lasting land-use change. In this dissertation, I have contributed an important case study that highlights the significant potential of restoration through agroforestry in Hawai‘i as well as the constraints to equitable participation in agroforestry transitions. Transferrable lessons emerge from this work and point to the need for more action-oriented, interdisciplinary research in partnership with stakeholders to inform not only the design and management of agroforestry systems themselves, but also the development of policies and programs that support more just and widespread agroforestry transitions.