UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAIʻI

Carbon benefits through fallow agricultural land transitions: the case of multi-strata agroforestry in Hawaiʻi

by

Leah L. Bremer, Gina McGuire, Zoe Hastings Silao, Natalie Kurashima, Tamara Ticktin, Susan E. Crow, Christian P. Giardina, Kawika B. Winter, Nathan DeMaagd, and Clay Trauernicht

Working Paper No. 2024-4
September 19, 2024

UNIVERSITY OF HAWAIʻI AT MANOA
2424 MAILE WAY, ROOM 540 • HONOLULU, HAWAIʻI 96822
WWW.UHERO.HAWAII.EDU

Carbon benefits through fallow agricultural land transitions: the case of multi-strata agroforestry in Hawaiʻi

Leah L. Bremer [1,2], Gina McGuire [3,4], Zoe Hastings Silao[4], Natalie Kurashima [5], Tamara Ticktin [6], Susan E. Crow [7], Christian P. Giardina [4], Kawika B. Winter [6,8], Nathan DeMaagd[1,7] ,Clay Trauernicht [7]

[1] University of Hawaiʻi Economic Research Organization, University of Hawaiʻi at Mānoa, Honolulu, HI, 96822
[2] Water Resources Research Center, University of Hawaiʻi at Mānoa, Honolulu, HI, 96822
[3] Department of Geography and Environment, University of Hawaiʻi at Mānoa, Honolulu, HI, 96822
[4] Institute of Pacific Islands Forestry, USDA Forest Service, Hilo, HI, 96720
[5] Kamehameha Schools, Kailua-Kona, HI, 96740
[6] School of Life Sciences, University of Hawaiʻi at Mānoa, Honolulu, HI, 96822
[7] Department of Natural Resources and Environmental Management, University of Hawaiʻi at Mānoa, Honolulu, HI, 96822
[8] Hawaiʻi Institute of Marine Biology, Kāneohe, HI, 96744

Abstract

There are growing efforts to incorporate agroforestry into ecosystem service incentive programs. Indigenous and other place-based multi-strata agroforestry systems are important conservation and agricultural strategies, yet their ecosystem services, including carbon sequestration benefits, have received little research attention. To fill this gap, we draw on interviews with agroforestry practitioners and ecosystem service modeling in Hawaiʻi to: 1) create future scenarios of where fallow agricultural lands and non-native dominated conservation lands could be transitioned to multi-strata agroforestry under current and future climates; and 2) quantify the potential above-ground carbon and soil carbon benefits and tradeoffs of transitions across these scenarios. Mean above-ground carbon in modeled agroforestry systems was estimated to be 92-125 Mg C ha^{-1} (337-458 Mg CO$_2$ ha^{-1}) with ~73% of the potential area significantly increasing above-ground carbon storage. Significant benefits for both above-ground and soil carbon are projected across 37-45% of the area transitioned to agroforestry, with just 4-5% of area with expected overall losses. With potential above-ground carbon sequestration similar or greater than that of native forest restoration, restoration through agroforestry represents an important pathway to achieving ecological, cultural, and economic benefits on large areas of fallow agricultural and non-native dominated conservation lands, offering a pathway to support inclusive and effective natural climate solutions.

Keywords: *nature-based solutions, payments for ecosystem services, soil carbon, above ground carbon, Indigenous land management, local values*

Introduction

There are growing efforts around the world to incorporate agroforestry systems in ecosystem service incentives, such as Payments for Ecosystem Services and other similar programs [1]. Agroforestry systems incorporate trees and crops or other tended and harvested products, and vary widely from several trees in a field to biodiverse, multi-strata systems [2]. Agroforestry, as a land-use option, continues to gain traction in agricultural-focused ecosystem service incentives, such as the United States Department of Agriculture's Environmental Quality Incentive Program (EQIP), in part because of their contribution to agricultural and biodiversity complexity of working landscapes [3]. Within forest-focused Payments for Ecosystem Services (PES) programs, agroforestry systems are increasingly seen as alternatives to removing land from production, which can have adverse social and ecological consequences, including loss of local management and livelihood systems [4]. PES programs in Latin America, for example, have added agroforestry systems as eligible for compensation in an effort to expand access and benefits of incentive programs for lower-income, smaller landholders, and rural communities, while providing numerous ecological benefits [4,5].

While the inclusion of agroforestry into ecosystem incentive programs is more recent, the practices that support agroforestry systems can be ancient - dating back in some cases millennia. Widespread, Indigenous agroforestry systems have long produced food, medicine, and fiber, increased or maintained tree cover, supported local biodiversity, and contributed to local livelihoods [6–9]. These approaches are based on generations of local knowledge, practices, and interests, and can offer important strategies for addressing concerns over justice and effectiveness raised in evaluations of ecosystem incentive programs and restoration efforts more broadly [4,10]. Improved equity and justice outcomes occur, in part, because Indigenous and place-based approaches inherently allow for local autonomy in design and placement, have community buy-in, and build on generational ecological and socio-cultural values [11,12].

The importance of Indigenous lands, knowledge, and practices has been elevated in the context of biodiversity conservation [13,14], and Indigenous rights are recognized as critical components of effective and equitable climate policy from local to international scales [15]. However, the potential of restoration through Indigenous and other place-based multi-strata agroforestry systems to contribute to climate mitigation (and reciprocally the potential ways that support for these systems could benefit local communities) remains under-studied [16]. This is despite recognition of the importance of agroforestry, in its broadest definition, as a natural climate solution [17,18]. Barriers to greater perpetuation and expansion of Indigenous and other place-based agroforestry practices include structural factors such as land tenure, resource availability, and need for appropriate recognition of Indigenous knowledge and cultural responsibilities [19]. A paucity of data on carbon sequestration potential of these systems also presents a barrier to entering into carbon focused incentive programs, which have the potential to support the expansion of agroforestry [20].

Hawaiʻi was the first state in the United States to commit to carbon neutrality [21], and provides many examples of restoration through Indigenous management practices, including agroforestry [12,19]. Hawaiian forests have also undergone vast environmental degradation, faces some of the highest resource management costs in the world, and there is a need to develop reforestation strategies that provide ecosystem services along with economic opportunities [22]. As such, Hawaiʻi provides an important case study to evaluate the potential for carbon sequestration of these practices to inform emerging carbon-based incentive programs focused on reforestation. In the current post-plantation, tourism-dependent economy, the decline of large colonial sugar and pineapple plantations alongside the high costs of land and labor facing farmers [23] has left approximately over 40% of agricultural lands fallow and often with degraded soils [24]. The challenging economics of agriculture in Hawaiʻi continue to perpetuate extremely high reliance on food imports [26]. Largely dominated by nonnative grasses, abandoned, unmanaged agricultural lands also create conditions of extreme fire risk [27] and are the leading cause of devastating fire events in the islands [27–29].

At the same time, Indigenous and other local community groups and practitioners are beginning to transition these lands to place-based multi-strata agroforestry systems to increase local food production while supporting a suite of societal values [19]. Multi-strata agroforestry tended for a suite of reciprocal benefits historically played a critical role in food production in Hawaiʻi [9,30]. These place-based systems were developed to meet local community needs while operating within environmental constraints, and often prioritized the protection of existing forest patches [31]. Today there is great potential for [9,30] and interest in [19] of multi-strata agroforestry across the state's fallow agricultural lands. These systems are also abundant across Pacific Islands and play critical roles in supporting communities and biodiversity [7,8,32,33], yet remain understudied. Given strong contemporary interest in managing and, where possible, mitigating GHG emissions, the potential of multi-strata agroforestry to sequester carbon is an important knowledge gap.

In this study, we describe the potential of agroforestry systems to sequester carbon across Hawaii's fallow agricultural lands, non-native dominated conservation lands, and undeveloped urban lands. In addition to the vast areas of fallow agricultural lands, an estimated 40% of areas zoned conservation across the state are dominated by non-native vegetation [34], offering important potential lands for agroforest restoration across vast areas of the islands [35]. We employ mixed methods including local and Indigenous practitioner interviews, literature review, and spatial modeling to: 1) build future scenarios of the potential for multi-strata agroforestry systems; and 2) estimate where both above-ground and soil carbon benefits and tradeoffs are most likely to accrue in order to explore the potential for multi-strata agroforestry to contribute to carbon sequestration in Hawaiʻi's under current and future climates. As Governmental, NGO, and private entities are rapidly mobilizing to initiate some of the first carbon credit projects [36], this is a critical and timely opportunity to facilitate the inclusion of these important land management practices that provide multiple ecological and social benefits and offer the potential to provide more durable carbon sequestration efforts.

2. Results

2.1 Agroforestry species mixes

We base our design of multi-strata agroforestry land use options on existing systems that are being tended across Hawaiʻi. These systems are site-specific and diverse relative to other agriculture in Hawaiʻi (>10 species per site), including both native and non-native, culturally important species [19]. While each agroforestry system is unique, common values motivate many people to practice multi-strata agroforestry, including restoring relationships to ʻāina (land), ancestors, and/or culture and strengthening local communities [19]. Hastings et al. (2021) found similar underlying values and motivations for practicing agroforestry, including to "reverse damage of plantation agriculture and ranching", because of "kuleana (responsibility) to ʻāina", to "feed our community", and for "community's health and wellness" as well as agroforestry specific themes such as to build on and perpetuate Indigenous and local knowledge and practices because "the template [for agroforestry] was created by our ancestors" and to "bring the forest back."

Figure 1: *Example multi-strata agroforestry systems in restoration today across Hawai'i include, Top left: dry system at Kahalu'u, Hawai'i Island [~6 years old], Top right: mesic system at Pu'ulani, He'eia, O'ahu [~4 years old]; bottom left: wet system at Honoli'i, Hawai'i Island [>10 years old]; bottom right: wet system at Waipā, Kaua'i [1 year-old system].*

Specifically, we designed three multi-strata agroforestry species mixes suitable for dry (500-1,500 mm/year), mesic (1,500-3,000 mm/year), and wet (>3000 mm/year) conditions based on common species tended by current practitioners in these rainfall zones and an understanding of 'Ōiwi (Native Hawaiian) agroforestry system types (Table SI.1). Species selected are only representative of the structure and diversity of current place-based multi-strata agroforestry in Hawai'i today; in practice, each system would likely contain a different mixture of the 137+ species mentioned in interviews representing 15 dry, 11 mesic, and four wet multi-strata agroforestry sites (Table SI.2).

2.2. Potential restoration area

Using current [37] and projected RCP 8.5 mid-century rainfall [38] for Hawai'i, we found a total of ~1,654 km^2 and 1,342 km^2 of potential restoration area across the state (Figure 2; Figure SI.1). We found that 91-92% of potential sites occurred on fallow agricultural lands (1,227-1,536 km^2), 6-8% on non-native dominated conservation lands (102-104 km^2), and the rest on undeveloped urban and agricultural lands (<1%). Under the current climate, 53%, 26%, and 21% of the restored area corresponds to dry, mesic, and wet MS agroforestry, respectively. With projected reductions in rainfall, there is a shift towards dryer systems (i.e., wet to mesic

(26 km^2); and mesic to dry (74km^2)) as well as a loss of 208 km^2 of potential restoration areas that drop below 550 mm/year.

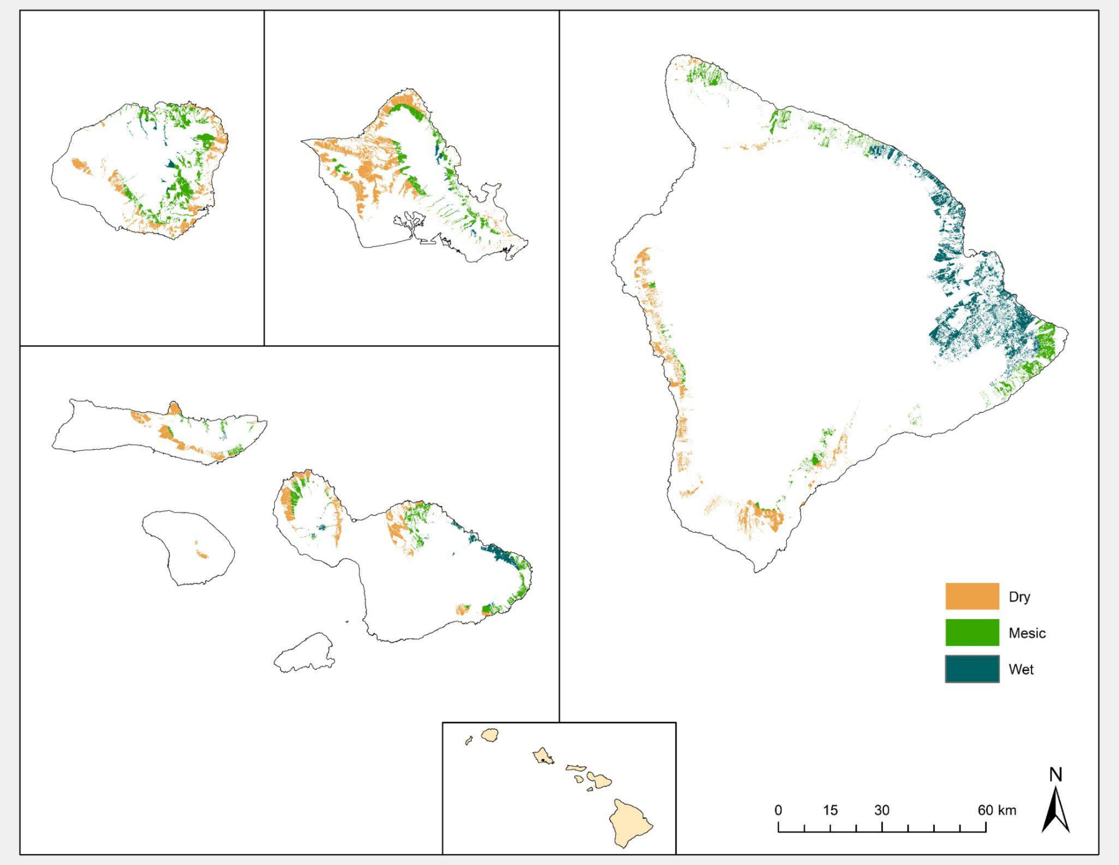

Figure 2: *Potential areas for restoration through multi-strata agroforestry under projected RCP 8.5 mid-century rainfall. See Figure SI.1 for current rainfall projections.*

3.2 Change in Above Ground Carbon

Per area mean above-ground carbon (AGC) was estimated to be 92-125 Mg C ha^{-1} (337-458 Mg CO_2 ha^{-1}; Table 2; Table SI.3) based on calibrations from our representative species mixes (Table SI.4).

System	**Mean** Mg C ha^{-1} (Mg CO^2/ha^{-1})	**Maximum** (Mg C ha^{-1} (Mg CO^2/ha^{-1})	**Minimum** (Mg C ha^{-1}/ Mg CO^2/ha^{-1})
Dry	97.5 (357.5)	131.3 (481.4)	63.4 (232.5)
Mesic	92.3 (338.4)	113.0 (414.3)	70.4 (258.1)
Wet	125.3 (459.4)	153.4 (562.5)	90.3 (331.1)

Table 2: *Mean AGC by agroforestry climate type. Note: In comparison, mean Mg C ha^{-1} of native dry forest = 6.6; invasive dry forest = 15.7; native wet-mesic = 72.4, invasive wet-mesic =90.9 (Selmants et al. 2017).*

Overall, 72% and 78% of the restoration area significantly increases in AGC under the current rainfall and RCP 8.5 mid-century rainfall respectively; in contrast, only 7% and 8% of areas show a significant decrease in AGC (Figure 3; Figure SI.2). The only areas without a significant increase in AGC are areas currently classified as non-native forest. The greatest gains in AGC are in transitions from sparsely vegetated areas, followed by grassland and shrubland areas, whereas transitions from non-native forest vary (Table 3).

Overall, if the entire restoration area was transitioned to agroforestry an average of 69.9 Mg C ha^{-1} (256.6 Mg CO$_2$ ha^{-1}) and 63.9 Mg C ha^{-1} (256.6 Mg CO$_2$ ha^{-1}) would be sequestered for a total of 11.6 million Mg (43.5 million Mg CO$_2$) and 8.6 million Mg C (31.5 million Mg CO$_2$) across the restoration area under current and RCP 8.5 mid-century rainfall projections, respectively. However, if only including areas with an expected increase (either trend increase or significant increase; 1,425 km^2 or 1,111 km^2) an average of 85.7 Mg C ha^{-1} (314.2 Mg CO$_2$ ha^{-1}) would be sequestered for a total of 12.2 million Mg C (44.7 million Mg CO$_2$ ha^{-1}) and 9.3 million Mg C (34.1 million Mg CO$_2$ ha^{-1} under current and future rainfall respectively. This later calculation, assuming a 20-year period of growth translates to an average sequestration rate of 15.7 Mg CO$_2$ ha^{-1} yr^{-1} and to 2.2 million Mg CO$_2$ yr^{-1} over the full transition area under the current climate and 1.7 million Mg CO$_2$ yr^{-1} under the future climate.

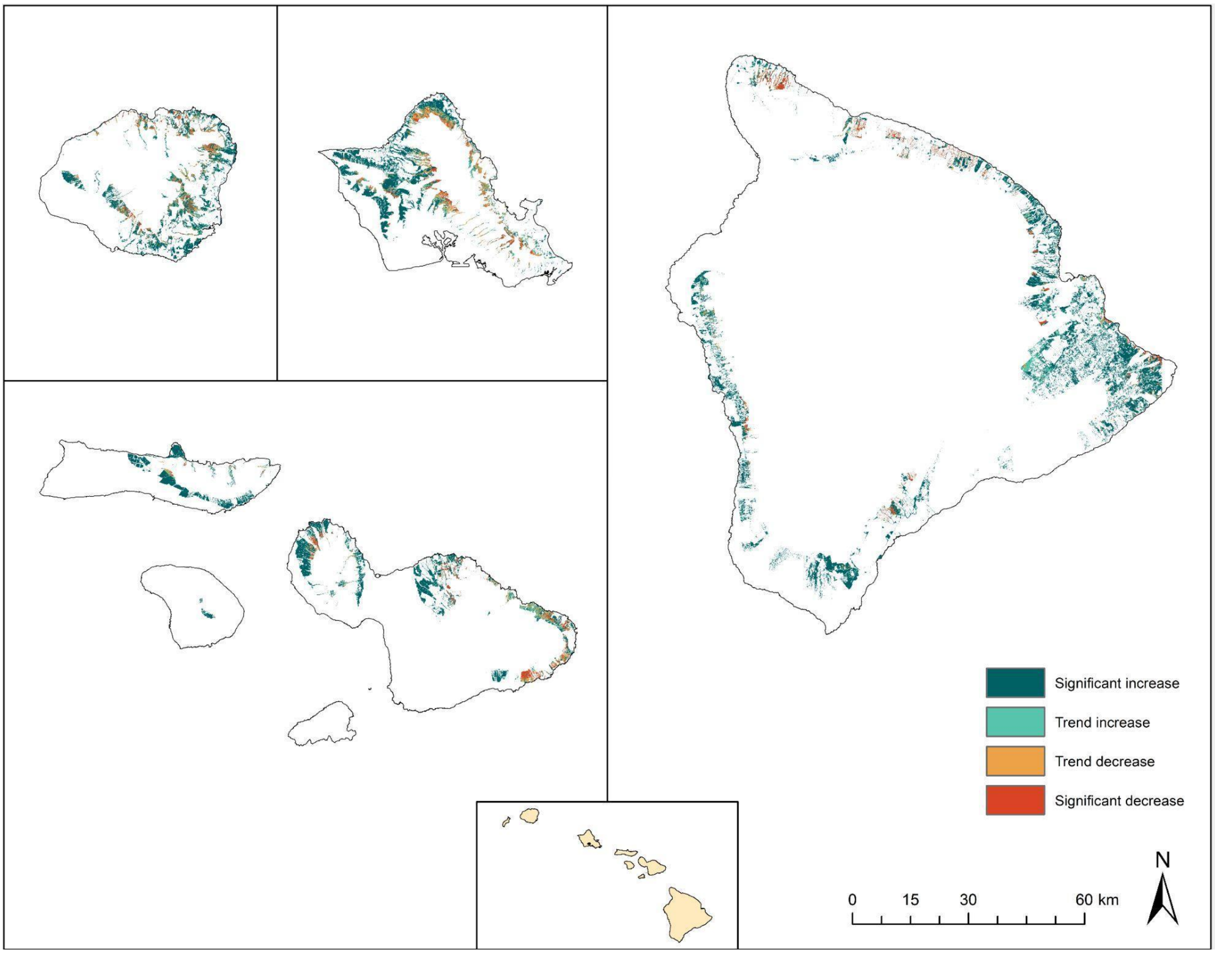

Figure 3: *Projected changes in AGC with restoration under RCP 8.5 mid-century rainfall. See Figure SI.2 for current climate projections.*

Initial land cover	**Mean change in AGC current climate**	**Area current climate (ha)**	**Mean change in AGC Under RCP**	**Area future climate (ha)**

	(Mg C ha^{-1}; SD)		**8.5 (Mg C ha^{-1}; SD)**	
Forest	17.9 (52.1)	619.5	12.7 (49.7)	579.8
Shrubland	94.1 (6.7)	277.1	94.2 (7.5)	156.2
Grassland	97.9 (11.4)	358.1	98.9 (12.2)	275.0
Sparsely veg.	105.4 (13.7)	399.8	107.1 (14.2)	331.5

Table 3: *Mean change in AGC (Mg C ha^{-1}) with a transition to multi-strata agroforestry by initial land cover type. SD=standard deviation*

3.3. Changes in Soil Carbon

Estimated changes in soil C are based primarily on data from global meta-analysis of soil C impacts of land use transitions to agroforestry [39–41]. These estimates show increases in soil C with transitions from cropland to agroforestry, but uncertain impacts with transitions from pasture or grassland. Across all types of agroforestry systems, transitions from forest to agroforest generally reduce soil C, but for the subgroup of multi-strata systems, Chaterjee et al. (2018) found forest to agroforestry transitions can increase soil C (see Table SI.5 for a summary of meta-analysis conclusions). Meta-analysis findings were complemented with directional changes found in specific studies, with a focus on either multi-strata agroforestry transitions in the tropics or from Hawai'i-based land use change studies matching the land-use transition climate zones and soil type [42]. About a third (i.e. 35 and 37% under the current and RCP 8.5 mid-century rainfall, respectively) of restored areas were projected to increase in soil C following a transition to multi-strata agroforest from intensive agriculture - primarily sugarcane and pineapple. Areas classified as "increase high confidence," corresponded to wet climates with poorly and non-crystalline mineral soils (Table SI.7) (PNCM; mainly andisols), which is also where the majority of land-use change studies have been done in Hawai'i (Figure 4; Figure SI.3; Table SI.8).

About a quarter (28% and 23% under the current and future climate, respectively) of restored areas were assessed as "no change", corresponding to areas where forest is transitioned to agroforestry. These were typically sites dominated by low activity clay soils in mesic systems and PNCM dry systems that have relevant local studies supporting no change in soil C and thus classified as "no change medium confidence" (Figure 4; Figure SI.3; Table SI.8), whereas the rest are classified as "no change low confidence."

Approximately 13% and 14% of modeled areas, under the current and future climate respectively, were classified as uncertain because of conflicting evidence, corresponding to pasture and grassland and reflecting the diversity in outcomes reported in global and local literatures. Finally, about a quarter (28% and 23% under the current and future climate respectively of modeled areas) were classified as unknown because of a lack of data, with these areas generally corresponding to shrubland and sparsely vegetated areas (Figure 4; Figure S1.4; Table SI.8).

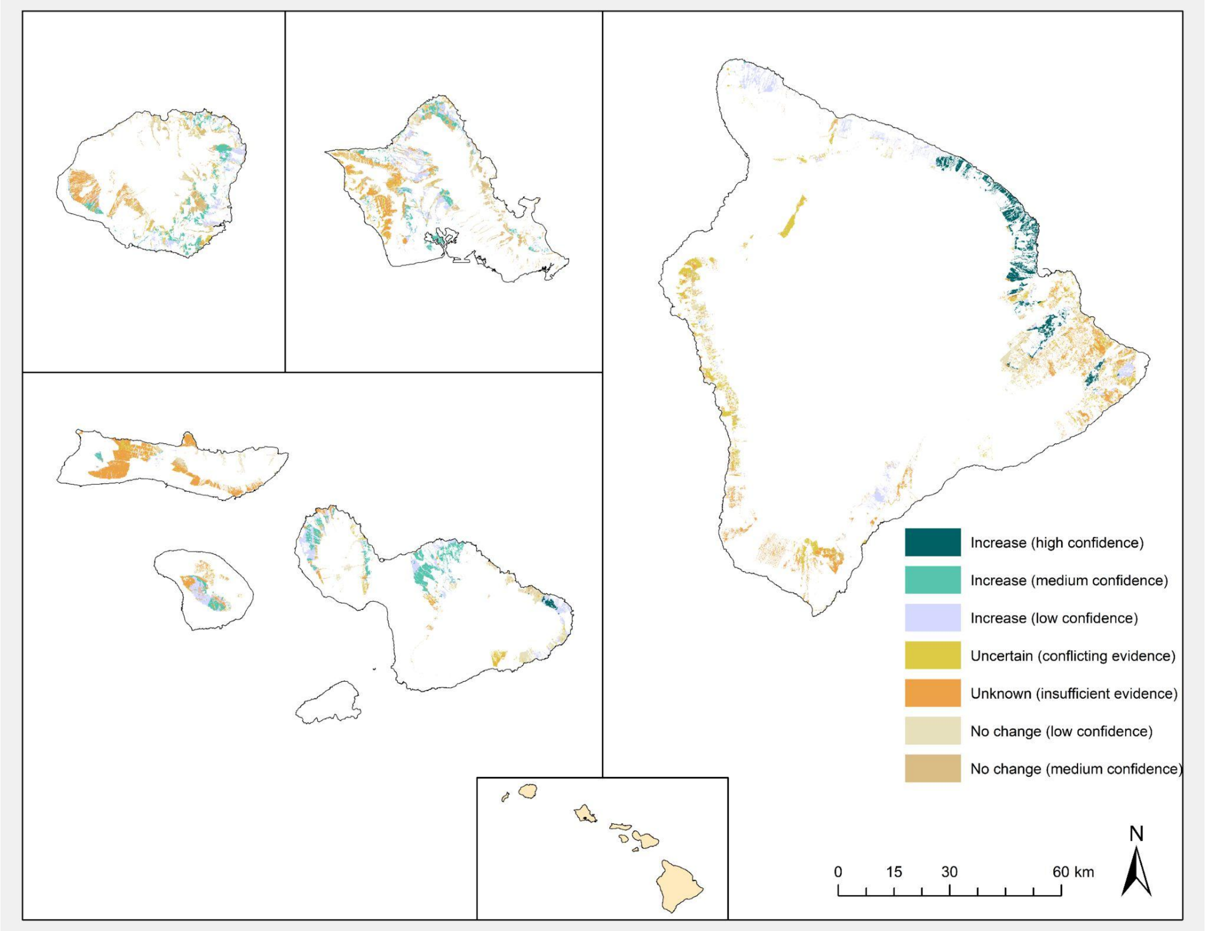

Figure 4: Projected changes in soil C under RCP 8.5 mid-century climate. See SI Fig. 3 for current climate projections.

3.4 Synergies & Tradeoffs of AGC & Soil C

Restoration is projected to significantly increase both soil C and AGC in ~28% of restoration areas. In another ~10% of the area, AGC increases significantly, but there is no change expected in soil C. Another 6% of areas are not expected to result in significant shifts in AGC, but are projected to increase in soil C. Together these three groups represent over a third of the restoration area (~43%) and are given a "green light," in that carbon benefits are highly certain to accrue with a transition to agroforestry. Conversely, only 4% of the areas are clear no-go zones where AGC is expected to significantly decrease and no change in SOC is expected (Figure 5; Figure S1.4; Table SI.9).

Another 35% and 41% of modeled areas, under current rainfall and future rainfall, respectively, can be considered "yellow" zones where more information is needed to understand the potential impacts of a transition to agroforestry on soil carbon. For these sites, current evidence is either uncertain (conflicting evidence) or unknown (insufficient evidence). This includes areas that are projected to significantly increase in AGC, with unclear impacts on soil C. Finally 3% of areas show a decrease in AGC, but a potential increase in soil C, representing non-native forest with intensive cultivation histories (Figure 5; Figure SI.4; Table SI.9).

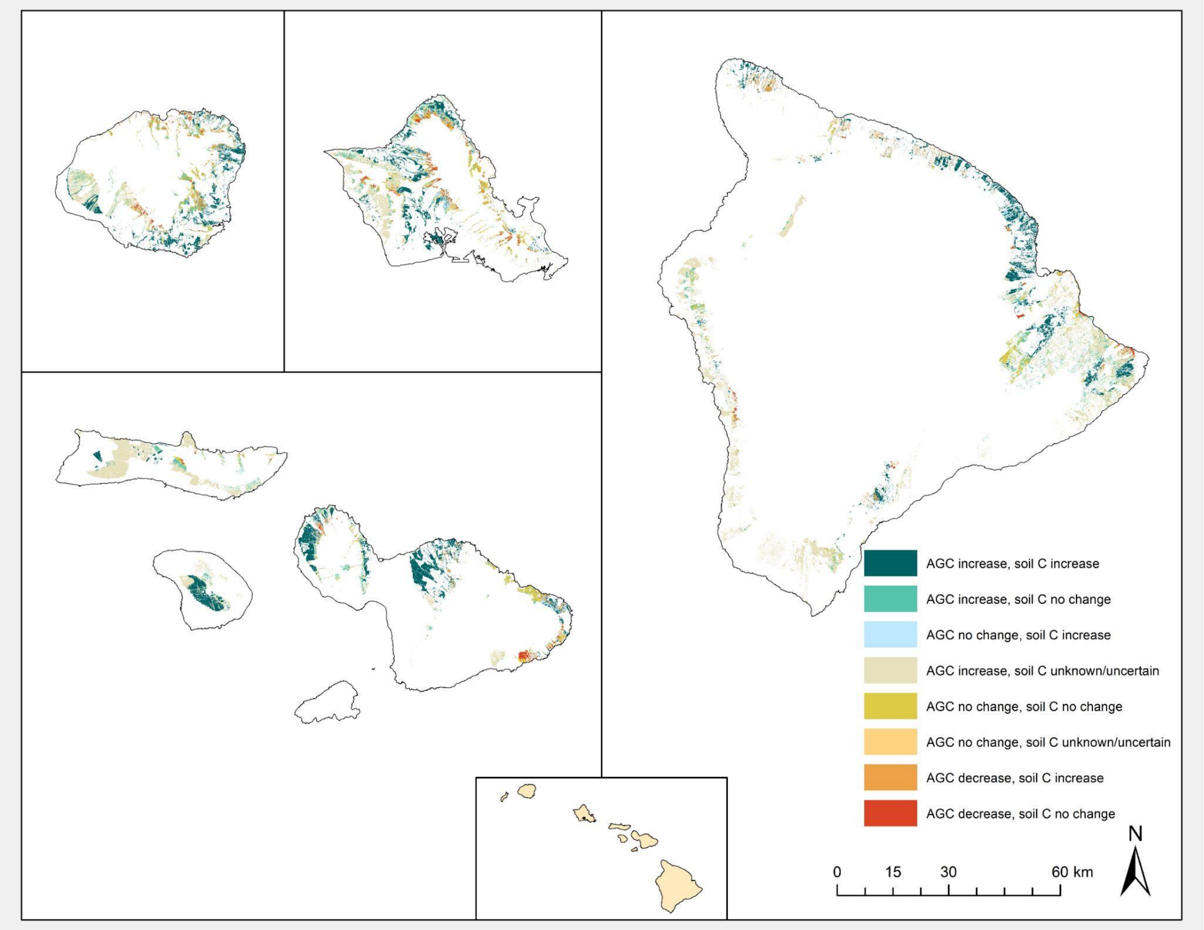

Figure 6: Projected synergies and tradeoffs in AGC and soil C with restoration under RCP 8.5 mid-century climate. See SI Fig. 3 for current climate projections.

3. Discussion

Place-based agroforestry systems have important potential as equitable and effective land-use practices in both agriculture and forest-focused carbon incentive programs. However, a paucity of data on carbon sequestration of place-based multi-strata systems can be an obstacle to their inclusion in these programs [1,43]. While agroforestry generally, and multi-strata agroforestry, in particular, is recognized as a promising natural climate solution in terms of carbon sequestration potential [18], estimates are globally variable and largely lacking for Hawai‘i and other Pacific islands [17,18,39]. We based our scenarios and carbon estimates on actual agroforestry systems being tended today by communities and other groups who support restoration through agroforestry because of a suite of interrelated social, cultural, ecological, and economic motivations [19]. Extending a previous effort to model the historical extent of colluvial agroforestry in Hawai‘i [9], we find that restoration through Indigenous and place-based multi-strata agroforestry is suitable across large areas of fallow agricultural lands and non-native dominated conservation lands. This is consistent with a recent modeling effort of a diversity of historical Indigenous agroforestry systems across Hawai‘i [30]. While we find that the potential restoration area decreases with a drying climate, there is still a substantial area of land suitable for restoration across these vast currently unmanaged lands.

An important modeling result is that nearly two thirds of the potential restoration area shows the potential for significant increases in above-ground carbon. The greatest gains, unsurprisingly, are in areas that are currently sparsely vegetated, grasslands, and shrublands.

Conversely, the lowest above-ground carbon gains, including losses, are in non-native forest to agroforest transitions. We also find substantial areas, primarily in current dry invasive forest areas, where transitions to agroforestry show increases in above-ground carbon even in areas that are currently forested. Our overall mean change in AGC with transitions to agroforestry is similar to mean estimates of multi-strata agroforestry carbon gains from available studies from Africa, Asia, and Latin America (79 Mg C ha^{-1}) [18,39]; our projected gains in AGC when restoring grasslands, shrublands, or sparsely vegetated areas are higher, whereas our estimates are lower when transitioning already forested land. Our mean estimates of potential AGC in agroforests are also higher than mean estimates of carbon stored in native dry and mesic-wet forest types [44], suggesting that agroforests offer an important reforestation strategy in areas that were traditionally and historically used for food production that can sequester relatively large amounts of carbon while also providing a suite of other benefits. A focus on fallow agricultural land also avoids land competition with other agricultural land uses, and agroforestry, as a food producing system itself, are in line with the activities of the agricultural land use district.

Another clear finding is that the greatest benefits for soil C will be in areas that were formerly intensively cultivated under plantation agriculture, representing over a third of the restoration area. This is in line with broader literature on the influence of both agroforestry and other reforestation projects on soil C [39–41,45], which suggest the greatest benefits where projects occur on cultivated or highly altered lands [46]. In Hawai‘i, the greatest benefits for overall carbon will be seen with restoration of invasive grasslands or sparsely vegetated non-native systems that were formerly in plantation agriculture given that high above-ground C and soil C gains are expected. These fallow grassland areas are also some of the areas now presenting the highest fire risk in Hawai‘i as a result of land use and climate drivers [47]. Given that replacing grasslands with closed-canopy woody vegetation is a key strategy to reducing fire risk [48], agroforestry presents a viable fire mitigation strategy while also sequestering carbon and providing broad social value to these lands. The economic and material benefits from agroforestry are providing incentives for communities elsewhere to integrate the practice as a fire risk strategy in economic and ecological contexts that have proven similarly difficult to manage [49].

Only 4-5% of the total area are considered “no go zones” where above-ground carbon is expected to decrease with uncertain or unknown benefits for soil C and another 14% with no expected change in soil C or AGC. These are predominantly in areas with non-native wet and mesic forests as well as unmanaged plantation forests (primarily *Eucalyptus* spp.) with higher or similar levels of above-ground carbon than agroforests, but that were never used for intensive agriculture. Whereas it makes little sense to prioritize restoring these areas through agroforestry for carbon sequestration benefits alone, transitioning non-native forests and unmanaged plantations to agroforestry is still be important for other objectives such as biodiversity, food production, and cultural benefits [35]. These non-native wet forests are one of the most difficult areas to find viable financing for land-use transitions and there is a need ot investigate alterantive, creative solutions, such as biochar. It is also important to note that some multi-strata agroforestry systems have been found to have similar to higher soil C than paired forests [40]. Thus, further research may shed light on the potential for soil C sequestration in this context [16] as well as other social and site-specific factors that may motivate people to transition their lands.

In other areas, including grasslands and shrublands which were never used for intensive agriculture, but often were used for pasture, there is wide uncertainty over the likely influence of transitions to agroforestry on soil C. In general, the global literature is mixed on the influence of reforestation and transitions from pasture or grassland to agroforestry in soil C [39–41,45], and there is little evidence for transitions from shrubland to agroforestry. However, given that above-ground C increases in these transitions, if soil C increases or stays the same, these areas would also be viable for carbon sequestration and likely expand the extent of positive carbon benefits. Overall, our study highlights gaps in understanding of the likely impact of transitions to multi-strata agroforestry on soil C across diverse land-use transitions, climate zones, and soil types (SI Table 3), but also demonstrates a method to incorporate qualitative directional change in soil C based on existing evidence.

Currently, nature-based carbon initiatives in Hawaiʻi are focused on restoring higher elevation pastures to koa (*Acacia koa*) because some growth and yield data and established silviculture practices exist for koa [50]. The species is also a fast growing, native keystone canopy species with high cultural and economic value. While these initiatives offer important opportunities in Hawaiʻi, there are vast lowland areas that have the potential for nature-based interventions and many different culturally relevant species that would provide similar C benefits. Agroforestry transitions in the lowland areas surrounding communities are a particular priority in the current context and urgent need to reduce fire risk on fallow agricultural lands [29]. In this context, restoration through agroforestry offers a land use strategy that produces food and other products on agriculturally zoned land, much of which is otherwise left unmanaged, posing enormous fire threat to homes and adjacent ecosystems. As Hawaiʻi confronts this problem after disastrous fires in 2023, combining carbon benefits with these other benefits may offer pathways to finance restoration of broad social value to these lands while also reducing fire risk. Moreover, prioritizing these fallow agricultural areas areas avoids tradeoffs in both C storage as well competing interests that often arise in reforestation and afforestation projects, such as impacts on native ecosystems and food production [51].

While our study advances understanding of the potential carbon sequestration benefits of Indigenous and other place-based multi-strata agroforestry systems, there are important uncertainties that require further research to refine estimates. In addition to the soil C uncertainties described above, above-ground carbon estimates are based on potential systems and use generalized allometric equations rather than specific allometric equations. Thus, developing species specific allometric equations to better estimate potential benefits over time will be critical for future work. As land use transitions to agroforestry systems continue to expand in Hawaiʻi and beyond, efforts to track changes in soil C and AGC over time will be imperative, but opportunities to do so will also increase. At the same time, work with practitioners to define priority areas for potential agroforestry transitions will inform where hotspots for carbon sequestration align with community goals and other factors influencing land use change. While a registered carbon project through the voluntary carbon marke in Hawaiʻi may be unlikely in the near future due to scale and data challenges, there are emerging ways to support carbon sequestration in these systems such as government funding mechanisms for readying underserved landowners in emerging ecosystem service markets.

4. Conclusion

We demonstrate the carbon sequestration potential of transitions to place-based multi-strata agroforestry on fallow agricultural and non-native dominant conservation lands across the Hawaiian Islands. By considering the spatial co-benefits and tradeoffs of AGC and soil C using local species assemblages, soil types, and climate regimes, we present an accessible and broadly generalizable approach to understanding ecosystem carbon potential for these multi-benefit systems using place-based practices. Investing in land management and restoration transitions up front is difficult for any restoration effort (including forest carbon projects). In this context, carbon credit revenue may be one way to help offset high initial upfront restoration cost over time. In the context of agroforestry systems, which require time to generate income, carbon incentives may help to complement revenue from harvests and other value-added products. On the other hand and over the long-term, the direct economic and cultural value derived from these systems may actually provide the incentives necessary to establish and maintain the broader societal benefits that other nature based solutions for carbon storage and fire risk reduction are struggling to finance.

An important additional question will be how to support place-based systems and local stewards at a scale amenable to carbon projects, which will likely entail addressing costs of land and tenure [19], building support networks across practitioners (e.g., malaoiwi.org), and exploring policies and economic programs that will facilitate these initiatives. Aggregated projects with multiple landowners is challenging, but there are successful examples (https://www.forestfoundation.org/what-we-do/increase-carbon-storage/family-forest-carbon-program/). While carbon will never be a primary motivation for these transitions, understanding the ways that carbon incentives can support this type of multi-benefit restoration leading to more effective and equitable outcomes is a critical part of just climate policy moving forward in Hawaiʻi and beyond. Carbon incentives can be conceptualized as one tool in the toolkit towards restoration. Though less data exist about complex multi-strata systems, it is clear they can have important soil and above-ground C benefits, while also being a multi-benefit land use that produces food, connects people to place, and provides increasingly important fire mitigation benefits.

4. Methods

4.1 Study Area

We examine the potential for multi-strata agroforestry restoration across the main Hawaiian Islands. Statewide, land is zoned either as conservation (~49%), agriculture (~46%), urban (~5%), or rural (<1%) [52]. Over 40% of agricultural lands are un-managed [24,25] and 40% of conservation lands are dominated by non-native vegetation [34], offering important potential lands for agroforest restoration across vast areas of the islands.

4.2 Potential agroforestry restoration scenarios

We first developed three land use options, or representative species mixes, of multi-strata agroforestry systems suitable for dry (550-1500 mm/yr), mesic (1,500-3,000 mm/yr), and wet (>3,000 mm/yr) rainfall zones [53]. We primarily based the agroforestry species mixes on interviews with multi-strata agroforestry practitioners from 30 sites across Hawaiʻi [19]. We analyzed semi-structured interview transcripts and extracted plant species mentions from each interview and noted any indication of the relative abundance of the species at the site. We identified the average annual rainfall of each site based on their location on the Hawaiʻi Rainfall Atlas [37] and categorized species as pertaining to dry, mesic, and wet systems according to the rainfall zones in Price & Jacobi (2012) (Table SI.1).

In the three land use options, we included species that were the most frequently mentioned across sites within each rainfall zone, and also took into consideration broader knowledge of the sites, from in-person visits since the interviews, and our team's collective knowledge of multi-strata agroforestry in Hawai‘i. We selected species adapted to the particular rainfall zone, assuming that irrigation would only be used in the establishment phase and potentially during severe drought (Table SI.1).

Although species composition of agroforestry systems is dynamic and successional, we developed the mixes based on the composition at maturity (>20 years since establishment). We estimated the total number of trees and shrubs per hectare in the mid- and overstory using the ‘four-layer complex’ pattern–the pattern most closely approximating multi-strata systems–in AgroforestryX, an online design tool developed for Pacific Island agroforestry systems that produces counts of trees in each layer for a 30 x 30 m plot [54]. Based on AgroforestryX, each 30 x 30 m plot included 189 overstory (mix of five species) and 200 midstory (mix of four species) individuals (Table SI.3). We combined the counts for the ‘emergent’ and ‘high’ layers given by AgroforestryX into one ‘overstory’ layer as pruning is the main factor distinguishing these layers [54], and this level of detail was not feasible to include in our model. For the midstory, we used the counts given for the ‘medium’ layer in AgroforestryX. We included the same number of species and number of trees across each rainfall zone.We assumed an understory layer of non-woody species whose compositions vary by climatic zone.

Spatial extent

We then projected where on the landscape each agroforestry type could be feasible under the current climate [37] and under a future climate scenario (Representative Concentration Pathway 8.5 mid-century) [38][1] (Figure 1). RCP 8.5 mid-century is based on statistical downscaling of Coupled Model Intercomparison Project phase 5 (CMIP5) for Hawai‘i, projecting an overall dryer climate, but greater contrasts between the wet and dry regions [38]. While initially considered extreme, RCP 8.5 is already expected to be overshot [55]. Accordingly, we use the current climate as a low-range potential future climate, and RCP 8.5 mid-century as a mid to upper range climate projection.

Most transitions to multi-strata agroforestry today occur when practitioners gain new access to primarily agricultural zoned land, in large part because of the history of Indigenous land dispossession and accumulation of land during the plantation era [56]. All 30 sites practicing multi-strata agroforestry Hastings et al. (2021) interviewed had a history of plantation agriculture or ranching and were fallow prior to undergoing restoration by practitioners. Prior to restoration, approximately half of the sites (n = 17), were dominated by non-native grasses, while the rest were restored from non-native secondary forest.

Accordingly, we assumed that multi-strata agroforestry transitions could occur on environmentally feasible land that was either: 1) zoned agriculture, but not used currently for agriculture (i.e., fallow or unmanaged); 2) zoned conservation, but considered low priority given a dominance of non-native species; 3) zoned urban, but undeveloped.

To determine unmanaged or fallow agricultural lands, we used a combination of the 2020 State of Hawai‘i Agricultural Baseline [24], which identified areas in active agricultural production, and state land use zoning maps which delimits agricultural zoned land [52]. Those lands zoned agriculture, but were not in production in 2020 were considered unmanaged

---

[1] We omitted Ni‘ihau from the analysis due to the lack of available data for soil and future climate data.

agricultural lands. Within these areas, we excluded any areas classified as developed or as native vegetation in the Hawaiʻi Carbon Assessment land cover map [57] and young lava flows [58]. Following the Kurashima et al. (2019) spatial model of colluvial agriculture (agroforestry) systems, we constrained the scenarios from sea level to 855 meters in line with crop growth restrictions and excluded areas with slopes over 30 degrees. We assumed multi-strata agroforestry would not occur below 550 mm rainfall per year, since long-term irrigation is often cost-prohibitive for agroforestry practitioners [19].

In addition to fallow agricultural lands, we also considered undeveloped urban and rural zoned areas as well as non-native dominated conservation zoned lands, which overlap with projections of suitable area for historical Indigenous colluvial agriculture (agroforestry) [9]. This aligns with several examples of agroforestry restoration on conservation lands dominated by invasive species [59], and on urban, but not developed lands [2].

4.3 Change in above-ground carbon (AGC)

We estimated the AGC (Mg C/ha) of trees in the overstory and midstory for the three types of multistrata agroforestry. We did not include understory species or shrubs in the AGC calculations given that the majority of AGC in Hawaiian forests are found in tree biomass [60] and the limited data available to include shrub and herbaceous biomass. Given the paucity of species-specific allometric equations for mature trees in our agroforestry land use options, we used a general allometric equation for tropical forest trees to estimate the above-ground carbon for a mature (~20 years) tree [61]:

$$AGB_{est}=0.0673\times(pD^2H)^{0.976}$$

Where D = diameter at breast height (DBH in cm), p = wood density (g/cm3), H = height (m) However, we used species-specific equations for two species that have tree growth forms, but are not woody: niu (*Cocos nucifera*; [62] and maiʻa (*Musa* spp.; Alcudia-Aguilar et al., 2019). All data and sources for height, DBH, and wood density values are in the supplementary material (Table SI.4; SI Methods).

We calculated a range of AGC estimates for each mult-istrata agroforestry type by varying the abundance of overstory and midstory species. We calculated AGC for 1) an even distribution of individuals across overstory and midstory species (i.e., average estimate), 2) a skewed distribution of individuals in which the three species with the highest carbon per tree in the overstory each made up 30% of the total trees in that layer and the two highest carbon trees in the midstory each making up 45% of the total individuals in that layer (i.e., maximum estimate), and 3) a skewed distribution of individuals such that the three species with the lowest carbon per tree in the overstory made up 30% and the midstory the top two 45% (i.e., minimum estimate) (Table S1.3). Due to the goals of the (high diversity, biocultural, etc.), we did not look at dominance of a single overstory species. Varying the distribution of species abundance in this way allowed us to estimate a range of values for AGC reflective of the diversity of planting designs followed by agroforestry practitioners.

Next, we assigned the AGC estimates for each multi-strata agroforestry type to the future spatial scenarios described in 2.1 to create a map of the potential AGC storage under potential agroforestry restoration. This was compared to a baseline AGC map, which combined an aboveground carbon density layer for forested lands in Hawaiʻi [63], and mean biomass estimates for non-forest lands in Hawaiʻi [44] (grassland = 2.5 Mg/ha; shrubland 4.4 Mg/ha). In order to incorporate a measure of uncertainty, only where the low range estimates exceeded the baseline AGC was the increase deemed significant. Likewise a decrease was considered significant where the high range estimate was lower than the baseline AGC.

4.4 Change in soil C

Given the complexity of shifts in soil C with land-use change and a lack of data on changes in soil C with agroforestry transitions in Hawaiʻi [16,64,65], we developed an approach to estimate the likelihood of directional change in soil C under varying combinations of initial land cover, soil type, and rainfall. As a first layer, we drew on a global meta-analysis of changes in soil C with agroforestry transitions [39–41]. These studies broadly find that soil C generally increases when transitioning intensive agriculture to agroforestry, decreases when transitioning from natural forest, and is mixed or no significant change with pasture or grassland transitions to agroforestry. Chaterjee et al. (2018) explicitly included data on transitions from agriculture and forests to multi-strata agroforestry systems in the lowland humid tropics and subtropics (15°N to 25°N and 15°S to 25°S), finding that multi-strata systems have more soil C than paired agricultural systems, and similar soil C compared to natural forests (see Table SI.6). De Stefano & Jacobson (2017) include agrisilviculture, which includes multi-strata systems, but also includes other systems including wind breaks and plantation crops.

There are several limitations of the meta-analyses. First, none of the meta-analyses includes comparisons of agroforestry to non-native forest or to shrublands. The analyses are also not disaggregated by soil type, which along with land use history and climate, likely influences the impacts that these transitions have on soil C [64,65]. Accordingly, we created a matrix and conducted a literature review on multi-strata agroforestry transitions classified by climate, soil type, agricultural land use history, and current land cover (Table SI.4). While there are no data on agroforestry transitions in Hawaiʻi, we also include land-use change studies in Hawaiʻi which compare cropland (sugar) or pasture to paired native forest as multi-strata forests are similar in structure to native forests. We describe each component of the matrix below.

Climate:
We used the rainfall zones described above to classify existing studies into: dry (550-1500 mm/yr), mesic (1,500-3,000 mm/yr), and wet (>3,000 mm/yr) rainfall zones [53].

Soil type:
Soil type groupings (Table SI.6) were delineated by spatial data developed for the Hawaiʻi Soil Atlas Order Series, "Fertility Class" layer. Based on Hawaiʻi Soil Atlas classifications [42] for mineral fertility class, soils were grouped as: high activity clays (HAC, including Mollisols, Vertisols, and Aridisols), low activity clays (LAC, including Oxisols and Ultisols), poorly and non-crystalline minerals (PNCM, including Andisols), and organic soils which include all histosols (HIST). Soils that did not fall into these categories include Entisols and Spodosols, which are classified as 'Other'. Inceptisols were grouped based on mineralogy (Table SI.6).

Agricultural land use history and land cover
Given the importance of the presence or absence of cultivation history in soil conditions, we classified any area with a history of intensive cultivation (primarily sugar and pineapple). To

do so, we used maps of historical sugar and pineapple lands, including the 1978-1980 Agricultural Land Use Maps (ALUM) [66] and the 2020 agricultural baseline [24]. If there was 'no production history' and/or a history of pasture, we used current land cover as the basis of comparison. Accordingly, we considered transitions from former agricultural lands, non-native forests, non-native shrublands, non-native grasslands, and from sparsely vegetated land.

Literature Review

We then considered whether each of the cells in the above-matrix (climate, soil type, agricultural history and land cover) has existing studies on multi-strata agroforestry transitions or from Hawaiʻi-based land cover studies.

To do so, we specifically considered:

1. Land-use change studies from Hawaiʻi comparing cropland or pasture to native forest or other restoration (including land uses that restore perennial vegetation without disruption of the belowground system) from the Hawaiʻi Soil Carbon Database [67].

2. Global studies of transitions to multi-strata agroforestry in tropical regions with similar climate and soil types. We extracted multi-strata agroforestry transition studies from, a meta-analysis of changes in soil C with agroforestry transitions globally [39–41]. Studies completed post-2018 and thus not included in the global meta-analyses were identified using Web of Science and Google Scholar using topic search (TS) term: TS= (soil carbon* + tropics OR agroforestry AND SOC* + tropics OR agroforestry). Abstracts were screened and articles included if they were located within tropical climates and involved a transition from intensive agriculture, non-native forest, shrubland, or grassland, or from sparsely vegetated land to multi-strata agroforestry.

Based on the literature available, we classified each point in the matrix in terms of the likelihood of directional change in soil C (Table 8). We classified studies as increase, decrease, no change, mixed evidence, or insufficient evidence.

	Criteria
Increase (HC)	Meta-analyses conclude significant increase AND more than two Hawaiʻi-based studies and/or tropical multi-strata studies find significant increase in soil C
Increase (MC)	Meta-analyses conclude significant increase AND 1-2 Hawaiʻi-based studies OR tropical multi-strata studies find significant increase in soil C
Increase (LC)	Meta-analyses conclude significant increase OR one or more Hawaiʻi-based OR tropical multi-strata studies find significant increase in soil C
No change (HC)	meta-analyses conclude no significant change AND more than two Hawaiʻi-based studies and/or tropical multi-strata studies find no significant difference in soil C
No change (MC)	Meta-analyses conclude no significant change AND 1-2 Hawaiʻi-based studies and/or tropical multistrata studies find no significant change in soil C;

No change (LC)	One or more Hawai‘i-based OR tropical multi-strata studies find no significant change in soil C
Decrease (HC)	Meta-analyses conclude significant decrase AND more than two Hawai‘i-based studies and/or tropical multi-strata studies find significant decrease in soil C
Decrease (MC)	Meta-analyses conclude significant decrease AND 1-2 Hawai‘i-based studies OR tropical multi-strata studies find significant decrease in soil C
Decrease (LC)	Meta-analyses conclude significant decrease OR one or more Hawai‘i-based OR tropical multi-strata studies find significant decrease in soil C
Uncertain (conflicting evidence)	Meta-analyses conclude no significant change OR existing Hawai‘i-based and tropical multistrata studies are conflicting
Unknown (Insufficient evidence)	No available data in Hawai‘i, tropical, & global studies AND no relevant meta-analysis comparison

Table 8: Rules to delineate projected soil C shift with transitions to agroforestry. Note: HC = high confidence; MC=medium confidence; LC=low confidence.

4.5. Tradeoffs in AGC and soil C

To evaluate the synergies and tradeoffs in soil C we characterized each pixel in the restoration scenarios as pertaining to an AGC category (AGC increase, AGC decrease, or AGC no change) and to a soil C category (soil C increase, soil C no change, or soil C uncertain/unknown). Pixels were only categorized as AGC increase or decrease if classified as significantly increasing or decreasing AGC (see section 4.3); otherwise they were categorized as AGC no change. No areas were projected to decrease soil C with restoration, so there were none classified as soil C decrease).

Acknowledgements:

We thank the agroforestry practitioners and community members who shared information about their practices, motivations, and species mixes. This paper is funded in part by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration, Project R/HE-38; which is sponsored by the University of Hawai'i Sea Grant College Program, SOEST, under Institutional Grant No., NA18OAR4170076 from NOAA Office of Sea Grant, Department of Commerce. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA or any of its subagencies. UNIHI-SEAGRANT-4918. This work was also funded, in part, by Kamehameha Schools.

Additional Information:

Authorship statement:

Conceptualization: LB, CT, TT, NK, ZH, KW; Funding acquisition: LB, TT, CT, KW, NK; Methodology: LB, GM, CT, ZH, SEC, CG; Analysis: LB, GM, CT, ZH, CT, ND; Writing (first draft): LB, GM, ZH; review: all authors.

Competing interests:
The authors declare no competing interests.

Data availability:
The datasets generated during and/or analyzed during the current study are available in the zenodo repository, [https://zenodo.org/records/11127213] and in the supplementary material.

References:

1. Nath, A. J., Nath, P. C. & Sileshi, G. W. Payment for Ecosystem Services from Agroforestry: Case Studies and Lessons. in *Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa* (eds. Dagar, J. C., Gupta, S. R. & Sileshi, G. W.) 739–757 (Springer Nature Singapore, Singapore, 2023). doi:10.1007/978-981-19-4602-8_23.
2. Hastings, Z. *et al.* Integrating co-production and functional trait approaches for inclusive and scalable restoration solutions. *Conserv. Sci. Pract.* (2020) doi:10.1111/csp2.250.
3. Cartwright, L. Using NRCS Technical and Financial Assistance for Agroforestry and Woody Crop Establishment through the Environmental Quality Incentives Program (EQIP). (2017).
4. Bremer, L. L. *et al.* Embedding local values in Payments for Ecosystem Services for transformative change. *Curr. Opin. Environ. Sustain.* **64**, 101354 (2023).
5. Shapiro-Garza, E. Contesting the market-based nature of Mexico’s national payments for ecosystem services programs: Four sites of articulation and hybridization. *Geoforum* **46**, 5–15 (2013).
6. Altieri, M. A. & Nicholls, C. I. Effects of agroforestry systems on the ecology and management of insect pest populations. in *Ecological Engineering for Pest Management* 143–154 (CSIRO, 2004).

7. Ticktin, T. *et al.* Linkages between measures of biodiversity and community resilience in Pacific Island agroforests. *Conserv. Biol.* **32**, 1085–1095 (2018).
8. Elevitch, C., Mazaroli, D. & Ragone, D. Agroforestry Standards for Regenerative Agriculture. *Sustainability* **10**, 3337 (2018).
9. Kurashima, N., Fortini, L. & Ticktin, T. The potential of indigenous agricultural food production under climate change in Hawaiʻi. *Nature Sustainability*, (2019).
10. Fleischman, F. *et al.* Pitfalls of Tree Planting Show Why We Need People-Centered Natural Climate Solutions. *BioScience* **70**, 947–950 (2020).
11. Di Sacco, A. *et al.* Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Glob. Change Biodivers.* **27**, 1328–2348 (2020).
12. Winter, K. B. *et al.* Ecomimicry in Indigenous resource management: optimizing ecosystem services to achieve resource abundance, with examples from Hawaiʻi. *Ecol. Soc.* **25**, (2020).
13. Garnett, S. T. *et al.* A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374 (2018).
14. Ogar, E., Peci, G. & Mustonen, T. Science Must Embrace Traditional and Indigenous Knowledge to Solve Our Biodiversity Crisis. *One Earth* (2020) doi:10.1016/j.oneear.2020.07.006.
15. Ramos-Castillo, A., Castellanos, E. J. & Galloway McLean, K. Indigenous peoples, local communities and climate change mitigation. *Clim. Change* **140**, 1–4 (2017).
16. Melone, A. *et al.* Assessing baseline carbon stocks for forest transitios: a case study of agroforestry restoration from Hawaiʻi. *Agriculture* **11**, (2021).
17. Chapman, M. *et al.* Large climate mitigation potential from adding trees to agricultural lands. *Glob. Change Biol.* **26**, 4357–4365 (2020).

18. Terasaki Hart, D. E. *et al.* Priority science can accelerate agroforestry as a natural climate solution. *Nat. Clim. Change* **13**, 1179–1190 (2023).
19. Hastings, Z., Wong, M. & Ticktin, T. Who Gets to Adopt? Contested Values Constrain Just Transitions to Agroforestry. *Front. Sustain. Food Syst.* **5**, (2021).
20. Nair, P. K. R., Nair, V. D., Kumar, B. M. & Schowalter, J. M. Carbon sequestration in agroforestry systems. *Adv. Agron.* (2010).
21. Selmants, P. C. *et al.* Ecosystem carbon balance in the Hawaiian Islands under different scenarios of future climate and land use change. *Environ. Res. Lett.* (2021) doi:10.1088/1748-9326/ac2347.
22. Burnett, K. M. *et al.* Restoring to the future: Environmental, cultural, and management trade-offs in historical versus hybrid restoration of a highly modified ecosystem. *Conserv. Lett.* (2018) doi:10.1111/conl.12606.
23. Suryanata, K., Mostafanezhad, M. & Milne, N. Becoming a new farmer: agrarianism and the contradictions of diverse economies. *Rural Sociol.* 1–26 (2020) doi:10.1111/ruso.12355.
24. Perroy, R. & Collier, E. 2020 Update to the Hawaiʻi Statewide Agricultural Land Use Baseline. (2021).
25. Melrose, J., Perroy, R., & Cares, S. *State Agricultural Land Use Baseline 2015. Hawaii Department of Agriculture.* https://hdoa.hawaii.gov/wp-content/uploads/2016/02/StateAgLandUseBaseline2015.pdf (2015).
26. Sudhakar, K. Food and Farming in Hawaiʻi a study of the obstacles to establishing resilient systems of local food production in Hawaiʻi. (Columbia University, 2020).
27. Trauernicht, C. Vegetation- rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on Big Island, Hawaiʻi. *Sci. Total Environ.* **650**, 459–469 (2019).

28. Nugent, A. D. *et al.* Fire and rain: the legacy of Hurricane Lane in Hawai‘i. *Am. Meteorol. Soc. BAMS* (2020) doi:10.1175/BAMS-D-19-0104.1.

29. Trauernicht, C. People not goats played a ‘central role’ in Maui wildfires. *Sci. E-Lett.* (2023).

30. Lincoln, N. K., Lee, T. M., Quintus, S., Haensel, T. P. & Chen, Q. Agroforestry Distribution and Contributions in Ancient Hawaiian Agriculture. *Hum. Ecol.* (2024) doi:10.1007/s10745-023-00471-4.

31. Lincoln, N. K., Haensel, T. P. & Lee, T. M. Modeling Hawaiian Agroecology: depicting traditional adaptation to the world’s most diverse environment. *Front. Sustain. Food Syst.* **7**, (2023).

32. McGuigan, A. *et al.* Post-cyclone resilience of an agroforest-based food system in the Pacific Islands. *Reg. Environ. Change* **22**, 57 (2022).

33. Thaman, R. Agrodeforestation and the loss of agrobiodiversity in the Pacific Islands: A call for conservation. *Pac. Conserv. Biol.* **20**, 180–192 (2014).

34. Potter, K. M. *et al.* How invaded are Hawaiian forests? Non-native understory tree dominance signals potential canopy replacement. *Landsc. Ecol.* **38**, 3903–3923 (2023).

35. Hastings, Z., Ticktin, T., Wong, M., Kukea-Shultz, K. & Bremer, L. L. Non-native fallows hold high potential for restoration through agroforestry in a Pacific Island ecosystem. *Agric. Ecosyst. Environ.* **342**, (2022).

36. Pacific Business News. Hawaii companies investing local carbon offset project. https://www.bizjournals.com/pacific/news/2019/09/23/hawaii-companies-invest-in-local-carbon-offset.html (2019).

37. Giambelluca, T. W. *et al.* Online Rainfall Atlas of Hawai‘i. *Bull. Og Am. Meteorol. Soc.* **94**, 313–316 (2013).

38. Elison Timm, O., Giambelluca, T. W. & Diaz, H. F. Statistical downscaling of rainfall changes in Hawai‘i based on the CMIP5 global model projections. *J. Geophys. Res. Atmospheres* (2015) doi:10.1002/2014JD22059.
39. Cardinael, R. *et al.* Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. *Environ. Res. Lett.* **13**, (2018).
40. Chaterjee, N., Nair, P. K. R., Chakraborty, S. & Nair, V. D. Changes in soil carbon stocks across the forest-agrofoest-agriculture/pasture continuum in various agroecological regions: a meta-analysis. *Agric. Ecosyst. Environ.* **266**, 55–67 (2018).
41. De Stefano, A. & Jacobson, M. G. soil carbon sequestration in agroforestry systems: a meta-analysis. *Agrofor. Syst.* (2017) doi:10.1007/s10457-017-0147-9.
42. Deenik, J. *et al.* Hawai‘i Soil Atlas. *Univ. Hawai‘i Coll. Trop. Agric. Hum. Resour.* (2014).
43. Hastings Silao, Z., Ocloo, X. S., Chapman, M., Hunt, L. & Stenger, K. Trends in agroforestry research over 4 decades. *Elem Sci Anth* **11**, 00151 (2023).
44. Selmants, P. C. *et al. Baseline Carbon Storage and Carbon Fluxes in Terrestrial Ecosystems of Hawai‘i*. (2017).
45. Guo, L. B. & Gifford, R. M. Soil carbon stocks and land use change: a meta analysis. *Glob. Change Biol.* **8**, 345–360 (2002).
46. Muleke, A. *et al.* Clarifying confusions over carbon conclusions: antecedent soil carbon drives gains realised following intervention. *Glob. Environ. Change Adv.* **1**, 100001 (2023).
47. Trauernicht, C. *et al.* The Contemporary Scale and Context of Wildfire in Hawai ‘i1. *Pac. Sci.* **69**, 427–444 (2015).

48. Wada, C. A. *et al.* Estimating Cost-Effectiveness of Hawaiian Dry Forest Restoration Using Spatial Changes in Water Yield and Landscape Flammability Under Climate Change1. *Pac. Sci.* **71**, 401–424 (2017).
49. Miller, M. A. Market-based commons: Social agroforestry, fire mitigation strategies, and green supply chains in Indonesia's peatlands. *Trans. Inst. Br. Geogr.* **47**, 77–91 (2022).
50. Baker, P. J., Scowcroft, P. G. & Ewel, J. J. *Koa (*Acacia Koa*) Ecology and Silviculture*. PSW-GTR-211 https://www.fs.usda.gov/treesearch/pubs/32152 (2009) doi:10.2737/PSW-GTR-211.
51. Doelman, J. C. *et al.* Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Change Biol.* **26**, 1576–1591 (2020).
52. State Land Use Commission. State Land Use District Boundaries. (2020).
53. Price, J. & Jacobi, J. D. Moisture zones for the main Hawaiian Islands. (2012).
54. Elevitch, C. R. & Logan, N. Agroforestry design tool. (2019).
55. Sanford, T., Frumhoff, P. C., Luers, A. & Gulledge, J. The climate policy narrative for a dangerously warming world. *Nat. Clim. Change* **4**, (2014).
56. Kameʻeleihiwa, L. Native Land and Foreign Desires: How Shall We Live in Harmony. *Bishop Museum Press, Honolulu, Hawaii* (1992).
57. Jacobi, J. D., Price, J. P., Fortini, L. B., Gon III, S. M. & Berkowitz, P. Carbon Assessment of Hawaiʻi Land Cover Map. (2017).
58. USGS. Geologic map of the State of Hawaiʻi.
59. Kamelamela, K. L. *et al.* Kōkua aku, kōkua mai: an Indigenous consensus-driven and place-based approach to community led dryland restoration and stewardship. *For. Ecol. Manag.* **506**, (2022).

60. Selmants, P., Litton, C., Giardina, C. & Asner, G. Ecosystem carbon storage does not vary with mean annual temperature in Hawaiian tropical montane wet forests. (2014) doi:10.1111/gcb.12636.
61. Chave, J. *et al.* Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob. Change Biol.* (2014).
62. Zahabu, E., Mugasha, A. W., Malimbwi, R. E. & Katani, J. Z. Allometric biomass and volume models for coconut trees. in *Allometric tree biomass and volume models in Tanzania* 107–116 (E & D Vision Publishing, 2018).
63. Asner, G. P. *et al.* Rapid forest carbon assessments of oceanic islands: a case study of the Hawaiian archipelago. *Carb. Bal. and Mngt.* **11**, (2016).
64. Crow, S. E. *et al.* The legacy of intensive agricultural history on the soil health of (sub)tropical landscapes. *Front. Env. Sci*. **10**, (2022).
65. Maaz, T. M. *et al.* Measuring the immeasurable: a structural equation modeling approach to assessing soil health. *Sci. Total Environ.* (2023) doi:10.1016/j.scitotenv.2023.161900.
66. State Department of Agriculture. Agricultural Land Use Maps (ALUM) 1978-2020. (2018).
67. Crow, S. E., Rivera-Zayas, J. & Viska, E. Hawaiʻi Soil Carbon Database. (2021) doi:10.17605/OSF.IO/HMTV6.

Supplementary Methods:

Above-ground Carbon:

We obtained DBH and height data first from two Pacific Island ethnobotanical and agricultural publications (Elevitch 2006, 2011), the book *Common Forest Trees of Hawai'i* (Little, Jr. and Skolmen 1989), and, if not available in any of those sources, the global, tropical Agroforestree Database (Orwa *et al.* 2009). For values that were given as a range at maturity (e.g., 8 - 10 m height), we calculated and used the mean of the given values. When data was not available in these publications, or only a maximum height or DBH was given, we used data from published case studies or knowledge from local experts. We extracted wood density data from the Tree Functional Attributes and Ecological Database (The International Council for Research in Agroforestry 2016). We used species means when available, and genus means for four species that were not in the database (i.e., *Metrosideros*, *Citrus*, *Santalum*, and *Pandanus*).

Supplementary Tables:

Table S1.1: ʻŌiwi (Native Hawaiian) agroforestry types and representative species mixes of dry, mesic, and wet multi-strata agroforestry systems in Hawaiʻi based on interviews from Hastings et al. (2021).

	ʻŌiwi agroforestry system types			**Dominant species in each land use option**		
	name	**range**	**description**	**overstory (> 8 m)**	**midstory (8 - 2.5 m)**	**understory (< 2.5 m)**
Dry multi-strata (550 - 1,500 mm / yr)	-	Kaupō, Maui	depression-planting within cinder/ash layers	ʻulu (*Artocarpus altilis*)^ koa (*Acacia koa*)+ niu (*Cocos nucifera*)^ avocado (*Persea americana*) wiliwili (*Erythrina sandwicensis*)+	cacao (*Theobroma cacao*) alaheʻe (*Psydrax odorata*)* ʻiliahi (*Santallum ellipticum*)+ tangerine (*Citrus reticulata*) ʻaʻaliʻi (*Dodonea viscosa*)* wauke (*Broussonetia papyrifera*)^	ipu (*Lagenaria siceraria*)^ lilikoi (*Passiflora edulis*) ʻuhaloa (*Waltheria indica*)* nīoi (*Capsicum frutescens*) lemongrass (*Cymbopogon citratus*)
Mesic multi-strata (1,500 - 3,000 mm / yr)	pāhala kauluʻulu	Puna, Hawaiʻi mesic midlands	hala, kalo agriculture practiced where tees/branches cleared (Handy & Handy 1972) mixed, open canopy dominated by ʻulu	ʻulu (*Artocarpus altilis*)^ koa (*Acacia koa*)+ niu (*Cocos nucifera*)^ kukui (*Aleurites moluccanus*)^ mango (*Mangifera indica*)	maiʻa (*Musa* spp.)^ coffee (*Coffea arabica*) lauhala (*Pandanus tectorius*)^ papaya (*Carica papaya*) māmaki (*Pipturus albidus*)+ kō (*Saccharum officinarum*)^	kalo (*Colocasia esculenta*)^ ʻōlena (*Curcuma domestica*)^ ʻuala (*Ipomoea batatas*)^ ʻawapuhi (*Zingiber zerumbet*)^ palapalai (*Microlepia strigosa*)* maile (*Alyxia stellata*)+

Wet multi-strata (> 3,000 mm / yr)	‘āpa‘a - pākukui	rainforest belt old-growth forest patchwork Hāmākua, Hawai‘i	native canopy is maintained, subcanopy altered highly tended forests to augment ecosystem services at landscape scale novel forest of kukui, swidden agriculture practiced where trees felled (Lincoln 2020)	‘ōhi‘a (*Metrosideros polymorpha*)+ kukui (*Aleurites moluccanus*)^ kamani (*Calophyllum inophyllum*)^ koa (*Acacia koa*)+ niu (*Cocos nucifera*)^	milo (*Thespesia populnea*)^ moringa (*Moringa oleifera*) ‘ōhi‘a ‘ai (*Syzygium malaccense*)^ kou (*Cordia subcordata*)^ hāpu‘u (*Cibotium* spp.) māmaki (*Pipturus albidus*)+	‘awa (*Piper methysticum*)^ ‘uluhe (*Dicranopteris linearis*)* kī (*Cordyline fruticosa*)^ kupukupu (*Nephrolepsis* spp.)* lau pele (*Abelmoschus manihot*) lauae (*Microsorum spectrum*)+

* *native*
\+ *endemic*
^ *Polynesian introduction*

Table SI.2: Full list of plants that agroforestry practitioners in Hawaiʻi mentioned growing during 30 interviews. Common names listed in the table are the terms referenced in the interview. These include general types of plants (e.g., vegetables), genera (e.g., citrus), and species (e.g., hala). Interview methods are described in Hastings et al. (2021).

Common name	**Species**	**Family**	**Number of interviews that referenced growing this plant at least once (n=30 interviews total)**
cacao	*Theobroma cacao*	Malvaceae	13
mai‘a	*Musa* spp.	Musaceae	13
‘ulu	*Artocarpus altilis*	Moraceae	12
kalo	*Colocasia* spp.	Araceae	12
koa	*Acacia koa*	Fabaceae	9
avocado	*Persea americana*	Lauraceae	8
māmaki	*Pipturus albidus*	Urticaceae	8
papaya	*Carica papaya*	Caricaceae	7
‘awa	*Piper methysticum*	Piperaceae	6
‘ōhi‘a	*Metrosideros polymorpha*	Myrtaceae	6
kukui	*Aleurites moluccanus*	Euphorbiaceae	6
mango	*Mangifera indica*	Anacardiaceae	6
niu	*Cocos nucifera*	Arecaceae	6
a‘ali‘i	*Dodonaea viscosa*	Sapindaceae	5
cassava	*Manihot esculenta*	Euphorbiaceae	5
coffee	*Coffea arabica*	Rubiaceae	5
kī	*Cordyline fruticosa*	Asparagaceae	5
kō	*Saccharum* spp.	Poaceae	5
‘olena	*Coprosoma waimeae*	Rubiaceae	4
‘uala	*Ipomoea batatas*	Convulvaceae	4
mahogany	*Swietenia macrophylla*	Meliaceae	4
milo	*Thespesia populnea*	Malvaceae	4
moringa (kalamungay)	*Moringa oleifera*	Moringaceae	4
neem	*Azadirachta indica*	Meliaceae	4
tangerine (mandarin)	*Citrus reticulata*	Rutaceae	4

alaheʻe	*Psydrax odorata*	Rubiaceae	3
awapuhi	*Zingiber zerumbet*	Zingiberaceae	3
cedro	*Cedrela odorata*	Meliaceae	3
gliricidia	*Gliricidia* spp.	Fabaceae	3
guava	*Guava* spp.	Myrtaceae	3
ʻōhiʻa ʻai	*Eugenia malaccensis*	Myrtaceae	3
lauhala	*Pandanus tectorius*	Pandanaceae	3
maile	*Alyxia stellata*	Apocynaceae	3
orange	*Citrus × sinensis*	Rutaceae	3
soursop	*Annona muricata*	Annonaceae	3
sunn hemp	*Crotalaria juncea*	Fabaceae	3
wauke	*Broussonetia papyrifera*	Moraceae	3
achiote (lipstick tree)	*Bixa orellana*	Bixaceae	2
bamboo		Poaceae	2
chaya	*Cnidoscolus aconitifolius*	Euphorbiaceae	2
chayote	*Sechium edule*	Cucurbitaceae	2
chili pepper	*Capsicum* spp.	Solanaceae	2
citrus	*Citrus* spp.	Rutaceae	2
diverse fruit trees			2
eucalyptus	*Eucalyptus* spp.	Myrtaceae	2
ʻiliahi	*Santalum ellipticum*	Santalaceae	2
kamani	*Calophyllum inophyllum*	Combretaceae	2
kupukupu	*Nehrolepis cordifolia*	Lomariopsidaceae	2
lau pele (bele, tongan cabbage, edible hibiscus)	*Abelmoschus manihot*	Malvaceae	2
lauaʻe	*Phymatosorus* spp.	Polypodiaceae	2
lemon	*Citrus lemon*	Rutaceae	2
lemongrass	*Cymbopogon citratus*	Poaceae	2
lilikoʻi	*Passiflora edulis*	Passifloraceae	2

lime	*Citrus spp.*	Rutaceae	2
macadamia nut	*Macadamia integrifolia*	Proteaceae	2
meyer lemon	*Citrus x meyeri*	Rutaceae	2
palapalai	*Microlepia strigosa*	Dennstaedtiaceae	2
peach palm	*Bactris gasipaes*	Arecaceae	2
perennial spinach / sisoo spinach	*Spinacia oleracea*	Amaranthaceae	2
pigeon pea	*Cajanus cajan*	Fabaceae	2
uhi / ube / yam	*Dioscorea alata*	Dioscoreaceae	2
wiliwili	*Erythrina sandwicensis*	Fabaceae	2
acai	*Euterpe oleracea*	Arecaceae	1
arugula	*Eruca vesicaria*	Brassicaceae	1
ashwaganda	*Withania somnifera*	Solanaceae	1
balsa wood	*Ochroma pyramidale*	Malvaceae	1
blue marble tree	*Elaeocarpus angustifolius*	Elaeocarpaceae	1
Burmese rosewood	*Pterocarpus indicus*	Fabaceae	1
butterfly pea	*Clitoria mariana*	Fabaceae	1
cantaloupe	*Cucumis melo*	Cucurbitaceae	1
carrots	*Daucus carota*	Apiaceae	1
cocoyam	*Xanthosoma sagittifolium*	Araceae	1
comfrey	*Symphytum officinale*	Boraginaceae	1
cordia	*Cordia spp.*	Boraginaceae	1
crown flower	*Calotropis gigantea*	Apocynaceae	1
dragonfruit	*Hylocereus undatus*	Cactaceae	1
durian	*Durio zibethinus*	Malvaceae	1
edible air potato	*Dioscorea bulbifera*	Dioscorea bulbifera	1
eggplants	*Solanum spp.*	Solanaceae	1
ginseng	*Panax ginseng*	Araliaceae	1

gourd tree	*Cucurbita sp.*	Cucurbitaceae	1
greens			1
guayusa	*Ilex spp.*	Aquifoliaceae	1
hāpuʻu	*Cibotium spp.*	Dicksoniaceae	1
herbs and spices			1
ʻilima	*Sida fallax*	Malvaceae	1
ʻukiʻuki	*Dianella sandwicensis*	Asphodelaceae	1
ʻūlei	*Osteomeles anthyllidifolia*	Rosaceae	1
ice cream bean	*Inga edulis*	Fabaceae	1
ipu	*Lagenaria siceraria*	Cucurbitaceae	1
jabong	*Citrus grandis*	Rutaceae	1
jabuticaba	*Plinia cauliflora*	Myrtaceae	1
Jamaican large leaf amaranth	*Amaranthus sp.*	Amaranthaceae	1
kale	*Brassica oleracea*	Brassicaceae	1
kamansi / breadnut	*Artocarpus camansi*	Moraceae	1
kauila	*Alphitonia ponderosa*	Rhamnaceae	1
kauri	*Agathis australis*	Araucariaceae	1
kou	*Cordia subcordata*	Boraginaceae	1
KX4 (Seedless Interspecific Hybrid Leucaena)	*Leucaena eucocephala X L. esculenta*	Fabaceae	1
lama	*Diospyros sandwicensis*	Ebenaceae	1
laurel	*Cordia alliodora*	Boraginaceae	1
lettuce	*Lactuca sativa*	Asteraceae	1
lima beans	*Phaseolus lunatus*	Fabaceae	1
long bean	*Vigna unguiculata*	Fabaceae	1
lychee	*Litchi chinensis*	Sapindaceae	1
madre de cacao	*Gliricidia sepium*	Fabaceae	1
maʻo hau hele	*Hibiscus brackenridgei*	Malvaceae	1

mamane	*Sophora chrysophylla*	Fabaceae	1
mountain yam	*Dioscorea polystachya*	Dioscoreaceae	1
mulberry	*Morus alba*	Moraceae	1
naio	*Myoporum sandwicense*	Scrophulariaceae	1
nasturtium	*Topaeolum*	Tropaeolaceae	1
noni	*Morinda citrifolia*	Rubiaceae	1
okra	*Abelmoschus esculentus*	Malvaceae	1
pāʻū o Hiʻiaka	*Jaquemontia ovalifolia*	Convolvulaceae	1
patchuli	*Pogostemon cablin*	Lamiaceae	1
perennial collards	*Brassica oleracea*	Brassicaceae	1
perennial peanut	*Arachis glabrata*	Fabaceae	1
pineapple	*Ananas comosus*	Bromeliaceae	1
podocarpus	*Podocarpus spp.*	Podocarpaceae	1
pōhuehue	*Ipomoea pes-caprae*	Convolvulaceae	1
pumpkin	*Curcurbita spp.*	Cucurbitaceae	1
red ginger	*Alpinia purpurata*	Zingiberaceae	1
santo tree	*Bulnesia sarmientoi*	Zygophyllaceae	1
sweet pepper	*Capsicum annuum*	Solanaceae	1
tabebuias	*Tabebuia spp.*	Bignoniaceae	1
tamarillo	*Solanum betaceum*	Solanaceae	1
teak	*Tectona grandis*	Lamiaceae	1
tomato	*Solanum lycopersicum*	Solanaceae	1
tree potato	*Solanum spp.*	Solanaceae	1
uhiuhi	*Caesalpinia kavaiense*	Fabaceae	1
uluhe	*Dicranopteris linearis*	Gleiceniaceae	1
vegetables			1
vesi (ifilele, pacific teak)	*Intsia bijuga*	Fabaceae	1
vetiver	*Chrysopogon zizanioides*	Poaceae	1

Table S1.3: *Summary of meta-analyses results of changes in soil C with transitions to agroforestry. Transitions are considered low-confidence in the directional change indicated with the meta-analyses if there are no studies within the specific soil classification, climate type, and land-use transition; medium confidence if there are 1-2 specific studies in agreement with the directional shift; and high confidence if there are 3 or more studies in agreement with the directional shift.*

Transition	**Chatterjee et al. 2018**	**De Stefano and Jacobson 2017**	**Cardinael et al. 2019**	**Summary**

Cropland to MS agroforestry	Across climates and AF[*] types, soil C in AF>cropland to 1 meter; soil C 40.6 % higher in MS systems than agriculture to 60 cm.	Across climates and AF types, soil C in AF>cropland; soil C ~40% higher in agrisilviculture than cropland at 0-30 cm and 10% higher at 0-100 cm	Across climates and AF systems, soil C greater in AF than croplands 0-30 cm.	Increase
Pasture/grassland to MS agroforestry	Across climates and AF types, varying response in soil C; no comparisons for MS systems, but in lowland humid tropics, soil C > in pasture than AF, but most comparisons are with silvopasture	Across climates and AF types, soil C in AF>grassland; soil C ~10% lower in agrisilviculture than grassland (0-60 cm)	Across climates and AF systems, no significant difference in soil C between pasture/grassland and AF	Uncertain (conflicting evidence)
Shrubland to MS agroforestry	No data	No data	No data	Unknown (insufficient evidence)
Secondary forest to MS agroforestry	Across climates and AF types, soil C in AF<forest to 1 meter; however, soil C is 20.4% higher in MS systems than forests to 60 cm	Across climates and AF types, soil C in forest>AF; soil C decreases ~28% with forest to agrisilviculture (0-30 cm); no significant decrease at 0-100 cm	Across climates and AF types, significant decrease in soil C in AF compared to forests	No change

[*] AF=agroforestry

Table SI.4: *Broad soil classifications for Hawai'i soils (based on Hawai'i Soil Atlas; Deenik et al. 2014).*

Soil Type	Soil Series

High activity clays (HAC)	Vertisols, Mollisols, Aridisols, Inceptisols without Oxic, Dystric, or Andic descriptors classified as 'fertile' in Hawai'i Soil Atlas
Low activity clays (LAC)	Oxisols, Ultisols, Inceptisols are LAC when with Oxic, Dystric, or Andic descriptors, classified as 'infertile' in Hawai'i Soil Atlas
Poorly and non-crystalline minerals (PNCM)	Andisols; inceptisols classified as 'other' in the Hawai'i Soil Atlas
Organic soils (HIST)	Histosols
Other	Entisols, Spodosols, and Alfisols

Table SI.5: *Summary of changes in soil C with transitions to agroforestry. Note that LC= low confidence, MC=medium confidence; HC=high confidence.*

	Current rainfall (% of restoration area)	**RCP 8.5 mid-century (% of restoration area)**
Increase LC	17	19
Increase MC	11	9
Increase HC	7	9
No change LC	17	22
No change MC	6	6
Unknown (insufficient evidence)	28	23
Uncertain (conflicting evidence)	14	13

Table SI.6: *Amount and percent of restoration area falling under each combination of soil and AGC benefits and tradeoffs. Descriptions in green indicate mutual benefits for soil C and AGC, yellow more uncertain overall benefits, and red clear tradeoffs.*

AGC and Soil C benefit/tradeoff	**Area (km2) current**	**Percent of area**	**Area (km2) RCP 8.5 mid-century**	**Percent of area**
AGC increase, soil C increase	*457*	*28*	*364*	*27*
ACG increase, soil C no change	*146*	*9*	*130*	*10*
AGC no change, soil C increase	*75*	*5*	*79*	*6*
AGC increase, soil C unknown/uncertain	*685*	*41*	*476*	*35*
AGC no change, soil C no change	*179*	*11*	*188*	*14*
AGC no change,soil C unknown/uncertain	*<1*	*<1*	*<1*	*<1*
AGC decrease, soil C increase	*50*	*3*	*47*	*3*
AGC decrease, SOC no change	*63*	*4*	*58*	*4*

=