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Assessing Baseline Carbon Stocks for Forest Transitions: A Case Study of Agroforestry Restoration from Hawai'i

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Citation: Melone, A.; Bremer, L.L.; Crow, S.E.; Hastings, Z.; Winter, K.B.; Ticktin, T.; Rii, Y.M.; Wong, M.; Kukea-Shultz, K.; Watson, S.J.; et al. Assessing Baseline Carbon Stocks for Forest Transitions: A Case Study of Agroforestry Restoration from Hawai'i. *Agriculture* **2021**, *11*, 189. <https://doi.org/10.3390/agriculture11030189>

Academic Editors: Marco Lauteri, Tommaso La Mantia and Anastasia Pantera

Received: 1 December 2020

Accepted: 19 February 2021

Published: 25 February 2021

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

Keywords: agroecology; biocultural restoration; soil carbon; ecosystem services; land-use change; equivalent soil mass method; sustainable development

1. Introduction

Secondary forests account for over 40% of existing tropical forest cover [1] and they are projected to dominate tropical landscapes into the future [2,3]. Secondary forests can support high biodiversity and provide other societal benefits including carbon storage, nutrient cycling, timber and non-timber forest products, cultural services, and wildlife habitat [4–6]. However, these benefits depend on the kind of forest transitions which

occur [7,8]. In some regions, particularly on islands, where invasive species dominate successional pathways [9,10], forest transitions often lead to novel ecosystems [11–13]. Novel ecosystems generally have relatively low native biodiversity but still can provide important ecosystem services [14–16]. Conservation and community-based efforts increasingly seek to improve the ecosystem services provided by these non-native, secondary forests through ecological restoration and hybrid approaches using a mix of native and non-native economic, cultural, and/or agricultural species [16–18]. In this context, it is critical to understand the current benefits these systems provide and how they change with management interventions.

In Hawai'i, non-native, secondary forest occupies 2200 km², or 40% of total forest cover, through post-commercial-agricultural succession and invasion into formerly native-dominated vegetation [19,20] as well as into forests formerly managed through Indigenous agroecology, including Indigenous agroforestry [21,22]. These forests have little conservation value, and threaten adjacent, native forest areas through the dispersal of non-native species, and negatively impact the biocultural value of landscapes [23–27]. Given the relatively low conservation, economic, or cultural value of these systems, limited natural resource conservation funding in Hawai'i has largely focused on protecting remaining native forest or restoring forest in higher elevation pastures [28–30]. However, there is increasing interest in targeting non-native, secondary forest for mixed systems of ecological restoration, including integrated forest-agricultural systems or agroforestry, especially as these sites are often in more accessible, lower elevation areas [17]. Assessing the impact of restoration approaches such as agroforestry requires the development of methods to adequately evaluate the change in ecosystem services and benefits over time as well as establishing baselines that characterize ecosystem services and other benefits currently provided by these secondary forests.

Agroforestry systems span a range of practices integrating trees and crops or other tended and harvested products and are gaining traction as an effective and equitable restoration strategy [17], including in the context of the Paris Climate Accord and other climate mitigation efforts [31]. Agroforestry has been practiced by Indigenous people for millennia [32–34], including on Pacific Islands where they are important sources of food and other plant production while also contributing to the conservation of native biodiversity and social-ecological resilience [35,36]. In Hawai'i, several forms of agroforestry, adapted to a broad range of conditions [36], alongside other forms of Indigenous agriculture, were found to have had the potential to produce enough food for >1 million people (similar to current population levels) at the turn of the 19th century [22]. While few agroforestry systems remain today in Hawai'i, there is great interest in their restoration to achieve multiple benefits including local food production, biodiversity, C storage, and cultural value [17,37–40], particularly as Hawai'i seeks to reach carbon neutrality by 2045 while simultaneously achieving a suite of other local sustainable development goals [41].

Several recent global meta-analyses have found clear evidence that agroforestry systems generally have higher soil C [42,43] and above-ground C [44,45] compared to conventional agriculture. In contrast, in aggregate, agroforestry systems generally have lower soil C compared to paired natural forests [42,43,46]. However, Chatterjee et al. [43] disaggregated this data by agroforestry system type and found a noted exception in lowland humid tropic multi-strata agroforestry systems, which stored similar to more soil C in the top 100 cm compared with paired natural forests. This was attributed to multi-strata systems mimicking natural forests and having equal or greater root litter C from understory and overstory species compared to forests [46–48]. While there has been no study comparing non-native secondary forests to multi-strata agroforests, existing evidence suggests multi-strata agroforests can have as much or more soil C than natural forests [43], and that multi-strata agroforestry restoration of secondary forests may have the potential to increase soil C over time, but assessing this change requires a careful methodological design.

In this study, we quantified the current carbon storage in a lowland secondary, novel forest system with low biodiversity (three dominant tree species; all non-native), where

a community-based non-profit is working to restore a biodiverse and culturally valuable multi-strata agroforestry system within the He'eia National Estuarine Research Reserve (NERR) [17,49]. The He'eia NERR is the first NERR established with the explicit goal of understanding the impact of biocultural restoration on ecosystem services, including C sequestration [49]. We carried out this baseline with the explicit goal of characterizing the spatial heterogeneity of soil C in order to accurately assess the current C stock of a secondary forest as well as to determine the required sample size to quantify changes in C over time as agroforestry restoration occurs. In contrast to the majority of studies on agroforestry land-use transitions, and of land-use change in general [47,48,50–52], our methodology focuses on characterizing both the horizontal and vertical heterogeneity of soil C concentration and stocks at very fine scale (i.e., meter to sub-meter). In line with calls to better understand C storage in agroecological systems [53–56], we use the equivalent soil mass (ESM) method [57] as a mass-based alternative to more prevalent bulk density (volumetric) dependent methods, which reduces problems of compaction related influences on C stock measurements [58–60]. We discuss results in terms of implications of future sampling design to characterize change in C storage, as well as the potential for soil C to also provide an indicator for a suite of on-and off-site benefits related to healthy soils and sustainable social-ecological systems.

2. Materials and Methods

2.1. Study Site

Our study site was within the ahupua'a (an Indigenous social-ecological community; [61] of He'eia where several community-based non-profit organizations collaborate to restore Native Hawaiian land management practices including wetland taro (lo'i kalo, *Colocasia esculenta*), loko i'a (traditional fish pond aquaculture), and more recently upland agroforestry systems (Figure 1) [17,49,62]. In 2017, part of the ahupua'a was designated as the He'eia National Estuarine Research Reserve (NERR) and is the first NERR specifically focusing on the restoration of social-ecological systems [49]. One of the primary goals of the NERR is to understand the potential of biocultural restoration to restore multiple ecosystem services [49]. Biocultural restoration refers to the mutually reinforcing restoration of land and culture [38,63,64].

We focused on an area within the He'eia NERR that is managed by the community-based non-profit Kāko'o 'Ōiwi, whose mission is to perpetuate the cultural and spiritual practices of Native Hawaiians. In collaboration with the University of Hawai'i at Mānoa, a ~4000 m² restoration area named Pu'ulani ("heavenly ridge") was selected as the first site of agroforestry restoration and a pilot to develop management and monitoring protocols [17]. Pu'ulani is a sloped ridge (25–30°), located 160 m above-sea-level with a mean annual rainfall of 1370 mm [65]. Over time, Kāko'o 'Ōiwi seeks to restore the entire ridge and a large upland area of over 80 ha of non-native forest to agroforest and native forest. At the time of sampling, Pu'ulani was composed of 100% non-native tree cover, dominated by Java plum (*Syzygium cumini*) with some fiddlewood (*Citharexylum spinosum*) and octopus tree (*Schefflera actinophylla*). The forest understory consisted primarily of bare-ground (leaf litter), basket grass (*Oplismenus hirtellus*), hilo grass (*Paspalum conjugatum*), and maile pilau (*Paederia foetida*) (Figure 2a). The future vision of the site as an ecologically, culturally, and economically valuable agroforest is depicted in Figure 2b. Plants in the future restored scenario includes overstory and mid-story species: koa (*Acacia koa*), pualoalo (*Hibiscus arnottianus*), loulu (*Prichardia* spp.), a'ali'i (*Dodonaea viscosa*), iholena lele (*Musa* spp.) a Hawaiian variety of banana as well as a variety of understory species including ilie'e (*Plumbago zeylanica*), pohinahina (*Vitex rotundifolia*), nanea (*Vigna mariana*), ahu'awa (*Cyprus javanicus*), and kupukupu (*Nepfrolepis cordifolia*) [see Hastings et al. [17] for a full description of restoration plan). The soils are classified as Ultisols (Loleka'a silty clay; LoB), though onsite soil classifications have not been done. Three 15 m × 12 m restoration plots (spaced 5 m apart), and expanding ~760 m² of the ridge composed the focal area of this study.

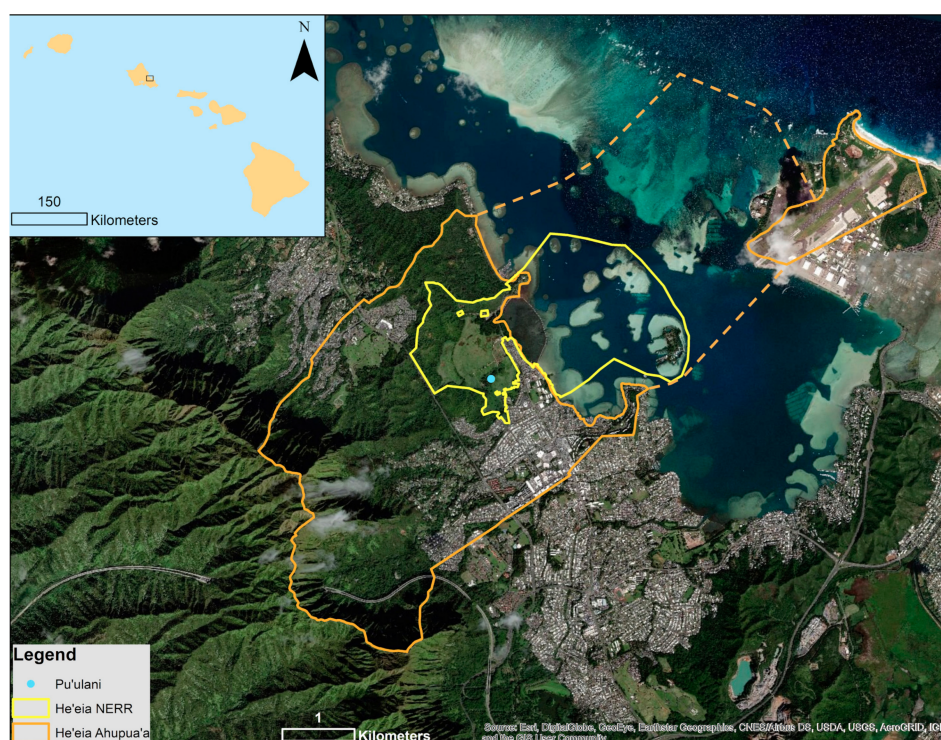


Figure 1. Pu'ulani agroforestry restoration site, in the He'eia ahupua'a, Ko'olaupoko, O'ahu. Noted: solid orange line represents ahupua'a boundaries in the Hawai'i Statewide GIS Program Ahupua'a GIS Layer. However, historical boundaries would have included the He'eia fishery within the ahupua'a boundaries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

2.2. Carbon Stock Measurement and Analysis

2.2.1. Vegetation Carbon

We quantified vegetation C following standard methods for trees, roots, coarse woody debris (CWD) and litter [19,66]. All trees within each plot were identified by species and measured for diameter at breast height. We used the generalized tropical forest allometric equation for above-ground biomass (AGB; Mg C/ha) [66]:

$$AGB = \exp[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673 \ln(D) - 0.0299 [\ln(D)]^2] \quad (1)$$

where, D = diameter at breast height (DBH; cm); ρ = wood density (g/cm^3), and E = a measure of environmental stress that increases with temperature seasonality, which corresponds to the duration of time a plant is exposed to stressful temperatures. A global gridded layer of E at 2.5 arc sec resolution was used from: http://chave.ups-tlse.fr/pantropical_allometry.htm (accessed on 25 February 2021). Wood density values were obtained from the tree functional attributes and ecological data base (<http://db.worldagroforestry.org/> (accessed on 25 February 2021)). We estimated below-ground coarse and fine root biomass as a function of above-ground biomass following Mokany et al. (2006) and as used in a study on Hawai'i Island [19,67]:

$$y = 0.489x^{0.890} \quad (2)$$

where, y is total root biomass and x is total above-ground biomass.

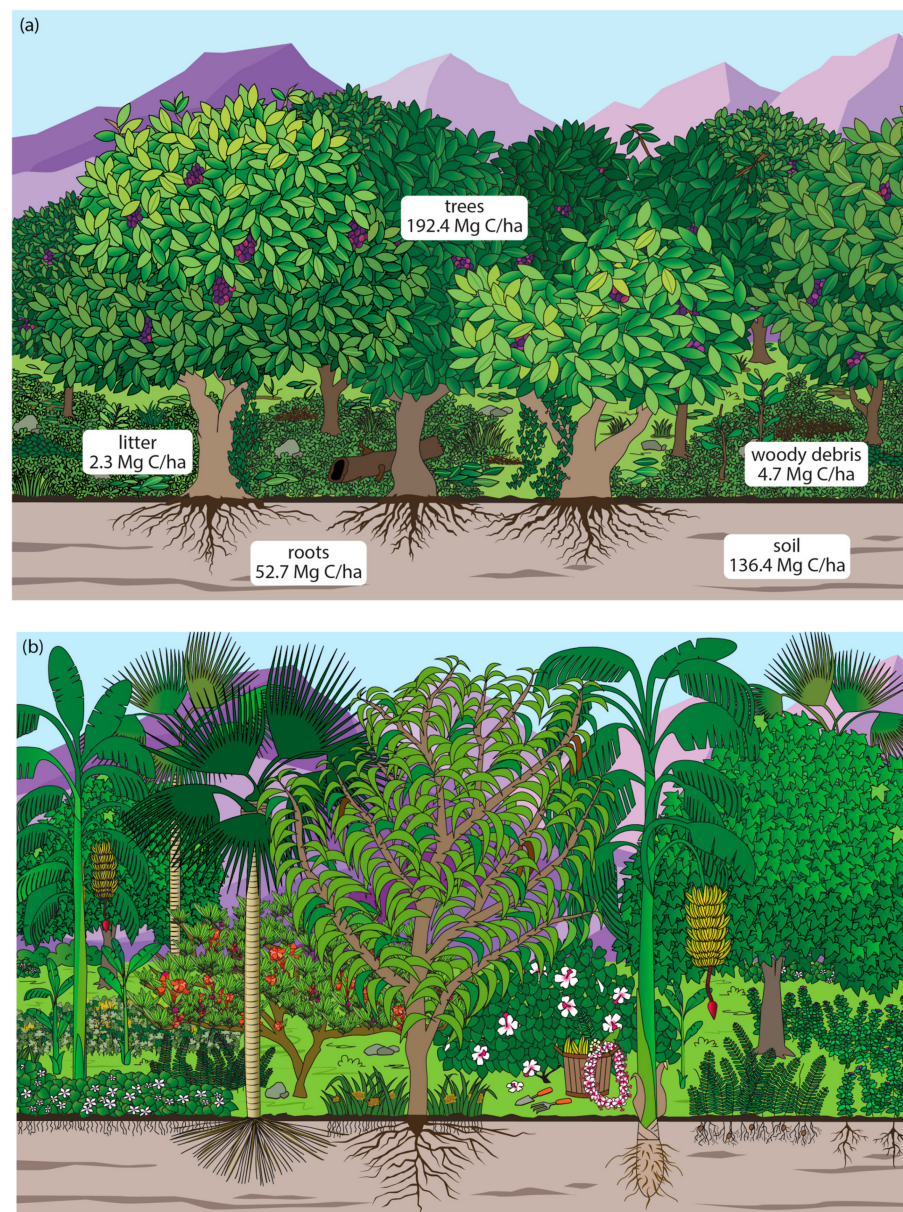


Figure 2. (a) Current non-native forest at Pu‘ulani prior to agroforestry restoration along with measured carbon stocks (Mg C/ha) in vegetation and soil. The current forest is dominated by the non-native Java plum (*Syzygium cumini*) tree; (b) Envisioned restoration of Pu‘ulani with a diversity of culturally, ecologically, and economically valuable plant species, including overstory and mid-story species: koa (*Acacia koa*), pualoalo (*Hibiscus arnottianus*), lolou (*Prichardia* spp.), a‘ali‘i (*Dodonaea viscosa*), kukui (*Aleurites moluccanus*), iholena lele (*Musa* spp.) a Hawaiian variety of banana, as well as a variety of understory species including ilie‘e (*Plumbago zeylanica*), pohinahina (*Vitex rotundifolia*), nanea (*Vigna mariana*), ahu‘awa (*Cyprus javanicus*), and kupukupu (*Nephrolepis cordifolia*) [see Hastings et al. [17] for details on restored scenario].

CWD, including standing or fallen dead wood >2 cm in diameter was measured [68]. We established four evenly spaced 15 m transects running down the slope within each plot, for a total of 12 transects. Along each transect, we measured the diameter of each CWD >2 cm which intersected the transect and classified it as fallen (at an <45° angle with the ground) or standing (>45° angle with the ground) debris >2 cm, which intersected the transect. There was only one piece of standing woody debris across all transects so we

combined this one measurement with the fallen debris. The volume of the CWD for each transect was then calculated as:

$$V = \pi^2 \sum d^2 / 8 \times L \quad (3)$$

where d = diameter (cm) of CWD where it intersects the transect, and L = length (m) of the transect.

To calculate CWD biomass from the volume each observed CWD was assigned a decay class of 1–4 (from solid fresh wood to rotten and friable wood) following Iwashita et al. [68], which quantified the wood density (ranging from 0.69–0.07) in similar conditions in Hawai'i. CWD biomass was then estimated as the product of CWD volume and the associated decay class-specific wood density. To estimate CWD C content from CWD biomass, CWD biomass was multiplied by the decay-specific % C estimates from Iwashita et al. [68] for each decay class (ranging from 46.3–47.7% C). The mean C (Mg C/ha) in CWD per plot was then calculated as the mean of the 4 transects.

Litter samples were collected in six-0.25 m² subplots randomly located within each plot. All litter within the subplot was collected and dried for 48 h at 65° to calculate the dry weight. Litter biomass was assumed to be 48% C [19].

2.2.2. Soil Carbon

To characterize the spatial heterogeneity of soil C, sixteen evenly spaced cores 3.75 m × 3.0 m apart were sampled using a grid within each 15 m × 12 m plot for a total of 48 soil cores over the three plots. Cores were sampled at five, 20 cm increments to a depth of 1 m. Each of the 20 cm increment samples were homogenized (mixed thoroughly) in the field post-extraction and the wet mass recorded. In the laboratory, soil samples were passed through a 2 mm sieve to remove all larger roots and rocks. Subsamples were oven-dried to a constant mass at 105 °C to determine moisture content, ground using a mortar and pestle, passed through a 250 µm sieve, and then analyzed for C concentration (% C) on a mass basis using an elemental analyzer (Carlo Erba Instruments NC 2500 Now Thermo Scientific, Waltham, MA, USA).

2.2.3. Carbon Stock–Equivalent Soil Mass Method

We used the Equivalent Soil Mass (ESM) method to quantify baseline soil C stock [57]. The ESM method is a mass-based approach for quantifying soil C stock using the cumulative mass of soil measured in the profile rather than the more widely used depth-based approach which relies on bulk density [69]. Land use and management directly impact bulk density and can bias comparative studies of C stocks over time or among treatments [60]. Instead, the ESM method is used to evaluate soil C stock in the context of land- use or management change [59], when processes such as compaction, tillage, and restoration of organic matter inputs are expected to change bulk density [57,60,70,71]. Curve fitting is used to develop a mathematical equation that describes the relationship between total soil mass and total carbon mass through each soil profile.

Following Wendt and Hauser [57], we fit quadratic polynomial equations to estimate the mass of C throughout each soil core. The specific reference mass used to make direct comparisons over time or between treatments is site-dependent and based on the mass of soil within each soil profile. As long as the reference mass chosen falls within the boundaries of the dataset collected for all profiles, any mass increment may be chosen for comparison and there is no limitation to the number of increments. We chose increments of 800 Mg/ha because (1) the average mass 20 cm samples across all plots was 830.3 Mg/ha, which makes the C stock roughly comparable to depth-based C stocks reported for the top 20 cm of soil and (2) all the cores had a mass of at least 4800 Mg/ha at the 1 m depth. Accordingly, we assigned the following mass increments: 800, 1600, 2400, 3200, 4000, and 4800 ESM intervals. The ESM of 4800 Mg/ha represented approximately ~80 cm of soil in this system, when averaged between the plots. We highlight both surface soil C (Mg C/ha, ESM 800) and deep soil C stock (Mg C/ha, ESM 4800) for this baseline assessment.

2.2.4. Geospatial Analysis and Kriging

Geospatial statistics have been used in soil science to quantitatively determine the spatial scales and patterns of soil characteristics, such as salinity, pollution by heavy metals, water content, nutrient content [72–75], as well as soil C following land-use change [76]. A common application of geospatial statistics is to interpolate soil properties as continuous surfaces over the landscape from point-based samples [77–79]. This approach relies on quantifying the spatial dependence among samples, or the relationship between the variability in sampled values and their location with respect to each other [72,80], which can then be used to infer scales of variation, or correlation ranges where observable change in soil properties can occur [74,75,77]. In addition, geospatial analysis can be used to inform subsequent spatial analysis (e.g., kriging and hybrid interpolation techniques) as well as guide future sampling [73]. The spatial dependence of soil C stock (ESM 4800) was quantified by plotting a variogram of the semivariance among pairs of sample points against the distance between them and fitting a Matérn model estimated by weighted least squares to the variogram. This relationship indicates the minimum semivariance, or nugget, which is the variance among immediately adjacent samples (i.e., due to random variation) as well as the range, which is the distance at which spatial dependence is no longer present among samples [75,81]. For our modeled variogram, we set the maximum distance between sample points to 20 m based on our plot area. This ensures the minimum number of pairs for the model and displays points for pairs of sample locations 20 m apart or less. Kriging, a form of optimum prediction, has been recognized as superior interpolation technique among many methodologies to make quantitative predictions at unsampled locations based on properties from nearby measured locations [82,83], with various applications in environmental science [75], including soil C [73,83–85]. The parameter estimates obtained from the variogram model fit were used in kriging operations to parameterize predictions of C values at unsampled locations within the plots [81,86]. Interpolated contour maps were produced by Bayesian kriging [86] displaying the vertical and horizontal heterogeneity of both C concentration and stock. Kriging enhanced the resolution by a factor of 15 from the original 48 cores sampled at ~20 m, and generated quantitative predictions at 752 new locations to produce interpolated contour maps at ~1.3 m resolution. These 752 values were predicted for both C concentration and C stocks (ESM 800 and ESM 4800). Contour maps were produced to characterize and display heterogeneity in soil C parameters.

3. Results

3.1. Ecosystem Carbon

Total ecosystem C across the three plots was 388.5 ± 18.6 (Mg C/ha \pm one standard error (SE)). Overall, C was highest in trees (192.4 ± 19.2 Mg C/ha; ~50% of total C); followed by soil (136.4 ± 7.9 Mg C/ha; ~35% of total C); roots (52.7 ± 4.7 Mg C/ha; ~14% of total C); and was the lowest in coarse woody debris (4.7 ± 2.8 Mg C/ha; ~1%) as well as litter (2.3 ± 0.2 Mg C/ha; <1% of total C) (Figure 2a; data available in Supplementary Information).

3.2. Soil Carbon

3.2.1. Percent Carbon

Mean soil C concentration decreased with depth across all plots from $6.1\% \text{ C} \pm 0.1\% \text{ C}$ in the surface samples (0–20 cm) to $1.2\% \text{ C} \pm 0.0\% \text{ C}$ in the deepest samples (80–100 cm; Figure 3). Contoured maps of C concentration also show a high degree of spatial heterogeneity within each depth (Figure 3a–e). For example, among surface samples (0–20 cm), C concentration varied from 1.7% C to 8.2% C with a notable area of high C concentration between plots 2 and 3 (Figure 3a).

3.2.2. Total Soil Carbon Stock

Mean soil C stock in the surface layer (ESM 800; roughly corresponding to 0–20 cm) was 50.3 ± 1.0 Mg C/ha (Figure 4a). Primarily due to the rapid decline soil C con-

centration, the mean soil C stock also declined with each ESM increment, lowering to 11.4 ± 0.2 Mg C/ha in the ESM 4000–4800 Mg/ha increment (Figure 4a). Mean cumulative soil C stock (ESM 4800; roughly corresponding to 0–80 cm) for the three plots was 136.4 ± 7.9 Mg C/ha (Figure 4b).

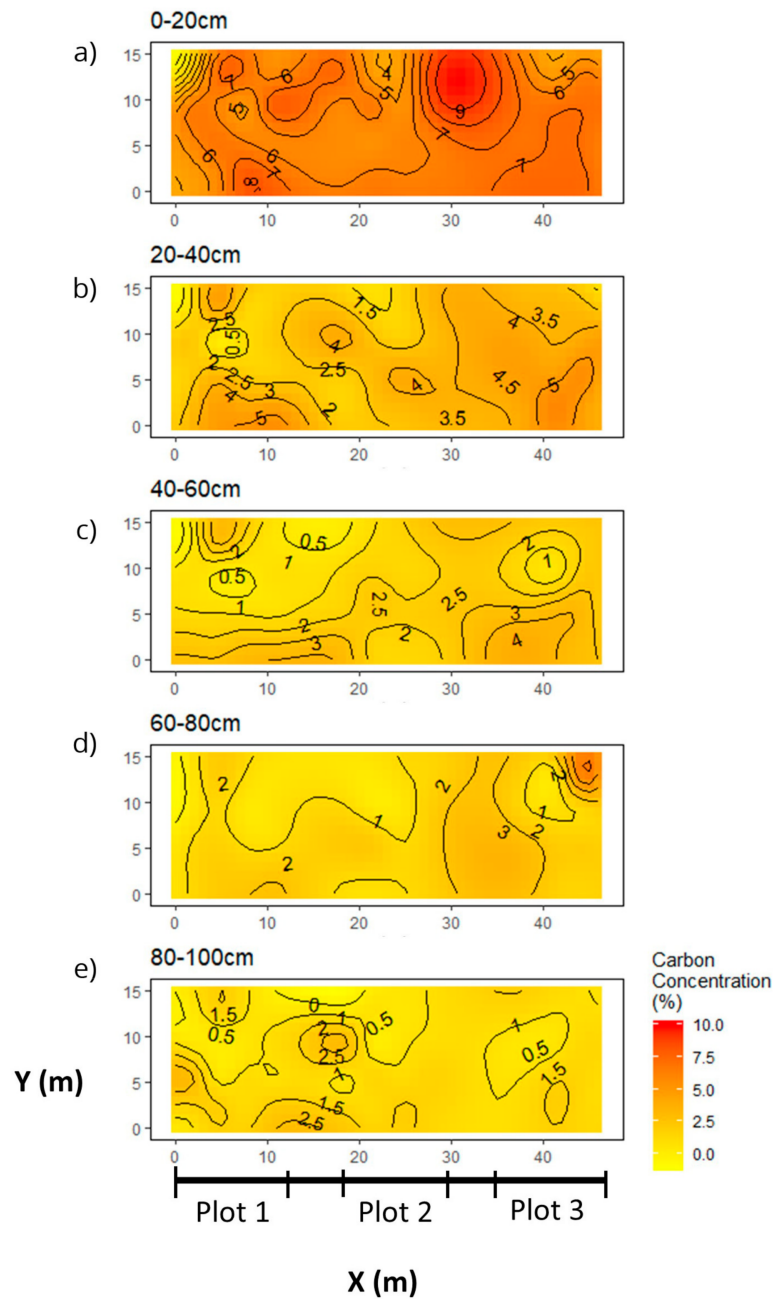


Figure 3. Interpolated contour maps of C concentration (% C) at each sampling depth demonstrating the lateral and vertical heterogeneity throughout the soil profile. (a) 0–20 cm; (b) 20–40 cm; (c) 40–60 cm; (d) 60–80 cm; (e) 80–100 cm. The y-axis is parallel to the slope of the ridge. The aspect of the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

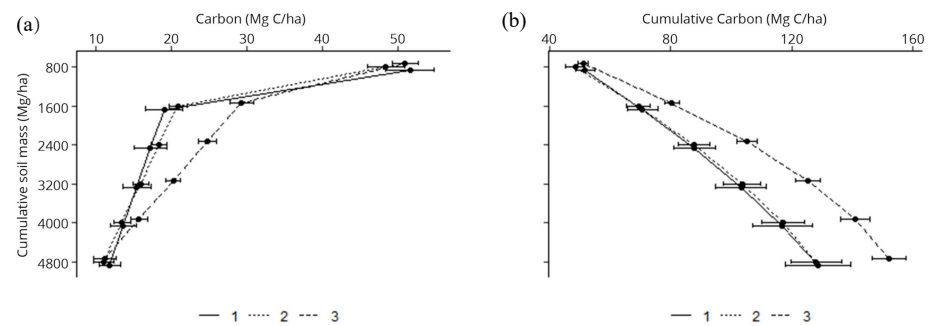


Figure 4. (a) Soil C stock (Mg C/ha) in each equivalent soil mass (ESM) increment of 800 Mg/ha and (b) cumulative soil C stock (Mg C/ha) for each plots. Points are plot means and error bars show \pm one standard error.

The spatial variability of the surface C stock (ESM 800; Figure 5a) follows similar distribution patterns as the surface soil C concentration. Kriged interpolations of deep soil C stock (ESM 4800; Figure 5b) reveal spatial heterogeneity in some places ranging from \sim 80–220 Mg C/ha within 8 m.

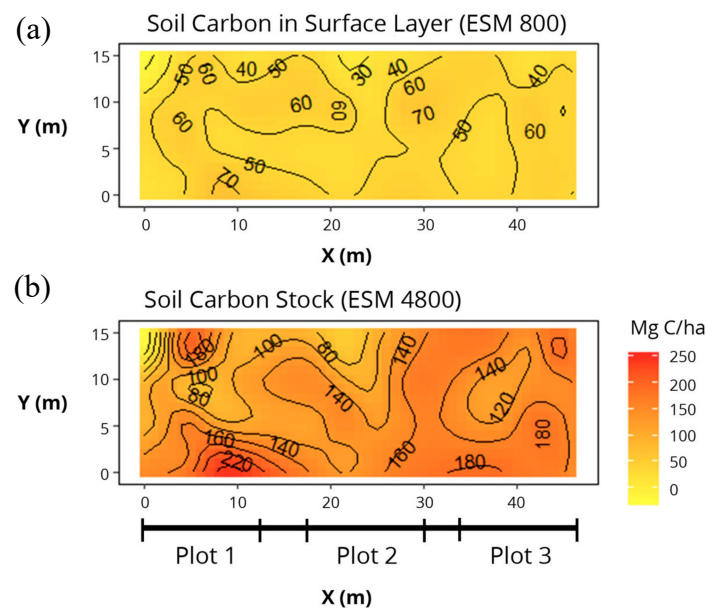


Figure 5. Interpolated soil C stock contour maps by Bayesian kriging of (a) surface soil C (Mg C/ha, ESM 800) and (b) deep soil C stock (Mg C/ha, ESM 4800). The y-axis is parallel to the slope of the ridge. The aspect of the slope is 117° for plot 1 and 130° for plots 2 and 3.

3.2.3. Spatial Dependence of Total C Stock

The computed variogram illustrates the soil C stock spatial relationships for 22 pairs of sample points (e.g., all point pairs ≤ 20 m apart). The range, or distance beyond which the sample values are spatially independent, is ~ 11.6 m, and is the location where the model prediction intersects the sill (Figure 6). The nugget, or variance among immediately adjacent samples was approximately 580 units of variance and the sill, or the maximum semivariance among samples, was approximately 1180 units of variance and is shown where the semivariogram model begins to flatten out (Figure 6). The ratio of the nugget to sill, a quantitative estimate of overall spatial dependence, was 49%, which is considered moderate for soil properties [77,87–89]. The 11.6 m value also can be interpreted as indicating samples collected more closely than 11.6 m are reporting similar information rather than new information.

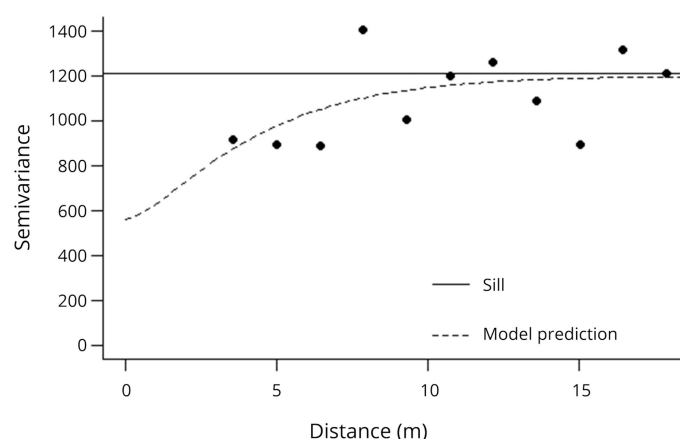


Figure 6. Variogram of total soil C stock (ESM 4800) for all pairs of sample points ≤ 20 m apart displaying the spatial dependence of the samples and displaying point pairs for sample locations 20 m apart or less. The best fit variogram model (Matérn model) with a smoothness parameter of 1 (the dotted line) estimates the nugget at 580, and the sill (solid line) at 1180, indicating a spatial dependence (nugget/sill) of 49%.

4. Discussion

This case study provides insight on current C storage in a novel secondary forest, a prevalent but poorly understood forest type in Hawai'i [9,90] and other parts of the tropics [3,91,92]. Quantifying soil C using the equivalent soil mass method as presented in this study can be applied in other areas, and the results provide insight into the spatial heterogeneity of soil C that can inform future sampling design. We discuss key insights and lessons from the results and methodology presented in this study and also highlight the importance of soil C as a potential indicator of restoration success in the context of biocultural restoration of an agroforestry system.

4.1. Lesson 1: Accurate Carbon Stock Assessment Requires Inclusion of Both Above- and Below-Ground Carbon Pools

Results of this study demonstrate the importance of including both above-ground and below-ground C in carbon assessments, echoing calls for greater attention to soil C in carbon assessments [76,93,94]. In our study area, $\sim 51\%$ of ecosystem C was stored above-ground in large non-native trees (primarily Java plum; *Syzygium cumini*), coarse woody debris, and leaf litter, while 49% was stored below-ground in soil and roots (of which soil C accounted for 35% of total C). Above-ground C (~ 199.4 Mg C/ha) was over twice as high as the mean above-ground C of wet-mesic non-native forests across the state (90.9 Mg C/ha) [20], although it was within the range of non-native forest dominated by large invasive trees including *Fraxinus uhdei* [90]. The high above-ground C found in this study is likely due to the low elevation and large java plum (*Syzygium cumini*) in this system, compared with many wet-mesic non-native forests across the state which are often dominated by smaller stature invasive trees such as strawberry guava (*Psidium cattleianum*) with lower carbon storage [90]. It must be emphasized that site-level biomass measurements are limited for non-native, secondary forest in Hawai'i [95], and thus these results contribute to our fundamental understanding of the variability inherent in these novel ecosystems.

In contrast, soil C at Pu'ulani was lower than the average soil C estimates (to 100 cm) across the state in wet-mesic non-native forests (136.4 ± 7.9 Mg C/ha compared to the statewide average of 180.5 Mg C/ha [20]). Soil C found at Pu'ulani is likely lower both due to the use of the ESM method, which resulted in using less than the full 100 cm sample (see discussion in 4.2) as well as to the fact that many wet-mesic non-native forests soils are Andisols, which store large amounts of soil C due to their biogeochemical properties [96,97]. However, compared with soils in the same classification in Hawai'i,

soils at Pu‘ulani exhibited high C concentrations. Soils in our sampling site are classified as Ultisols (Loleka‘a silty clay), for which the original type location data describes this soil as having 3.2% C in 0–25 cm and 0.6% C in 84–107 cm depths [98]. In comparison to the type location data, the percent C at Pu‘ulani was substantially higher at comparable depths (6.1% C in 0–20 cm and 1.2% C 80–100 cm respectively).

4.2. Lesson 2: The Equivalent Soil Mass Method (ESM) Provides a Practical Mass-Based Method to Characterize Soil C Stocks at Depth

Second, our results reiterate the importance of sampling at depth (~100 cm) using a quantitative method—the equivalent soil mass method (ESM)—designed specifically for assessing land-use change [57,60]. Such sampling is increasingly called for to better understand current C stocks and change with land-use transitions [53,56,76,99]. While the majority (63%) of soil C in this study was in the surface layer (ESM 800), there was a substantial portion of soil C in the subsurface soil (in the ESM increments 1600, 2400, 3200, 4000, and 4800). This is a similar magnitude to other studies which have found that globally subsurface soil (30–100 cm) contains an average of 47% of the entire soil C stock [100]. Often inadequately characterized in C studies, these deeper soil layers can hold more persistent C pools (i.e., stabilized and stored for a longer time), but can also be affected by land-use change [99,101–103]. Deeper sampling is becoming more common [102] as there is increasing recognition of microbial interactions that affect C storage dynamics even below a 100 cm depth [104,105]. While the ESM provides an alternative to bulk-density dependent methods which can be unreliable in the context of land-use change [57], it is important to note that it is advisable to sample to depths greater than 100 cm (or the desired depth) in order to capture the full profile as the ESM is limited by the samples with the lowest mass. In the case of this study, our last ESM (ESM 4800) constituted an average of ~80 cm depth given the lower mass of some samples.

4.3. Lesson 3: Geospatial Analysis Can Effectively Characterize Spatial Heterogeneity and Inform Future Sampling Effort

Third, we demonstrate the use of geospatial analyses to characterize the heterogeneity of C in a secondary forest system. The nugget to sill ratio of the semivariogram (Figure 6), a measure of spatial dependence, was 49% which is within the moderate range for soil properties [77,87–89]. From the perspective of future sampling, the range of the semivariogram in this study indicated that samples further away than ~11.6 m are spatially independent. Thus, if future sampling requires statistically independent samples to, for example, test for differences in plot-level treatments, the range indicates the minimum distance to maintain between soil samples. In contrast, for repeat robust spatial interpolation as we have performed here, a sampling interval of ~5.8 m or less (half of the semivariogram range) is recommended [106,107]. These results indicate that we could reduce future sampling intensity from a grid of $n = 16$ to $n = 9$ in each plot and still adequately interpolate the data.

The interpolated contour maps by kriging (Figures 3 and 5) display both vertical and horizontal heterogeneity of soil C concentration and C stock. Surface soils (i.e., to 0–20 cm and ESM 800 respectively) not only contained the highest C concentrations and majority of C mass, but were also the most spatially heterogeneous and variable, with values ranging over an order of magnitude (Figure 3). Quantification of spatial variability of soil properties is more often conducted for large areas [73,108,109], while this study provides evidence of small-scale spatial variability of soil C and importance of fine scale sampling [110].

4.4. Lesson 4: Soil Carbon Is More Than Just the Ecosystem Service of Climate Mitigation; It Can Serve as a Holistic Indicator of Success in Biocultural Restoration of Agroforestry Systems

Over time, as our study system in He‘eia moves from a monoculture invasive tree dominated system to a diverse and multi-strata agroforestry system (Figure 2), soil C storage may increase over the long-term, though a decline in soil C may occur in the early years of restoration due to initial clearing and planting disturbance [44]. As with a variety of diversified agricultural systems, multi-strata agroforestry systems are often

designed and managed in ways that increase soil organic matter or soil C (e.g., through composting, crop rotation, perennial vegetation with greater root inputs), which in addition to the ecosystem service of C sequestration, also underpins a suite of other on- and off-site ecosystem services, including increased crop yields, resilience to pests, and water retention capacity [39,53,111]. Soil C is also an indicator of soil fertility and can reduce the need for external inputs, making the system itself more self-sustaining, which is often a goal of agroforestry [42,43,53,112,113]. These ecosystem system benefits are particularly relevant for organizations like Kāko'o 'Ōiwi and the He'eia NERR who seek to restore multi-functional Indigenous agricultural systems using a biocultural approach [49], which favor low external inputs and high functional and species diversity [17]. The species selected for restoration all provide important linked cultural and ecological value and rely on healthy soils to thrive. A critical metric for success is an increased connection of community to the forest [17], and soil C will be central in this vision as a critical indicator of the ability of the system to thrive and contribute to multiple local sustainable development goals, including local food production, carbon sequestration, and biodiversity protection [41].

5. Conclusions

As the area of tropical secondary forests continues to expand, so will efforts to enhance the ecosystem services provided by these systems. This case study from Hawai'i provides a methodology for documenting baseline C storage in a non-native secondary forest, with widespread application to other restoration projects seeking to assess this benefit alongside others cultural, ecological, and economic benefits. It also provides foundational information on C quantity and heterogeneity in an ecosystem in Hawai'i that is poorly studied despite its large extent across the islands. We demonstrate the importance of including both above- and below-ground carbon stocks as ~49% of ecosystem C was found below-ground (in soil and roots), including ~35% in the top ~80 cm of soil. Using the equivalent soil mass method, which provides a metric less sensitive to future land-use change, we also confirm the value of sampling beyond surface depths, as ~37% of soil C was found in subsurface (~20–80 cm) layers. Finally, we demonstrate the utility of geospatial methods to quantify the spatial heterogeneity of soil C, which can provide insight into appropriate sampling design for monitoring. As the biocultural restoration of this site continues, these results additionally suggest that soil C can be a useful indicator of soil health, which underpins a suite of on and off-site ecosystem services, thereby contributing to a range of both local and global sustainable development goals.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2077-0472/11/3/189/s1>, Supplementary Information.

Author Contributions: Conceptualization, L.L.B., S.E.C., T.T., Z.H., A.M., C.T., K.K.-S.; methodology, S.E.C., L.L.B., A.M.; field work, A.M., L.L.B., M.W., Z.H., S.J.W.; lab analysis, A.M., M.W., S.E.C.; formal analysis, A.M., C.T., L.L.B., S.E.C.; writing—original draft preparation, A.M., L.L.B.; writing—review and editing, A.M., L.L.B., S.E.C., C.T., Z.H., T.T., M.W., K.K.-S., S.J.W., Y.M.R., K.B.W.; visualization, A.M., C.T., S.E.C., Y.M.R., L.L.B.; supervision, L.L.B., S.E.C., C.T., K.B.W., Y.M.R.; funding acquisition, L.L.B., T.T., C.T., K.B.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by: (1) the Natural Resources Conservation Service, Conservation Innovation Grant #NR18925190002G003; (2) the University of Hawai'i Social Science Research Institute Research Support Grant; (3) Office for Coastal Management, National Ocean Service, National Oceanic and Atmospheric Administration Grant 11.420, Coastal Zone Management Estuarine Research Reserves Award ID#s NA19NOS4200078 and NA20NOS4200095; (4) grant/cooperative agreement from the National Oceanic and Atmospheric Administration, Project R/HE-38, which is sponsored by the University of Hawaii Sea Grant College Program, SOEST, under Institutional Grant No. NA18OAR4170076 from NOAA Office of Sea Grant, Department of Commerce. UNIHISEAGRANT-JC-20-04.; (5) the National Science Foundation EPSCoR Award No. OIA #1557349; (6) the USDA National Institute of Food and Agriculture, Hatch project # HAW1151-H, managed by the College of Tropical Agriculture and Human Resources at the University of Hawai'i at Mānoa; (7) and

the USDA NIFA Renewable Natural Resources Extension Act; 8) NSF Graduate Research Fellowship (#1842402; Z.H). The views in this paper are the authors' and do not necessarily reflect those of the funding organizations or sub-agencies.

Data Availability Statement: All carbon data presented is available as supplementary material.

Acknowledgments: We would like to acknowledge: Russell Yost for providing expertise on geospatial and geostatistical analysis and reporting znc Amanda Toperoff with Big Blue Animation and Design lab for generating the pre- and post-restoration depiction. We also thank Paul Selmants for assistance with above-ground carbon sampling design; Christine Tallamy-Glazer, Jon Wells, Elaine Vizka and Casey McGrath of the Crow lab for assistance sampling, laboratory, and data analysis; and Jade Delevaux, Gina McGuire, and Victoria Ward for assistance with figures. We also thank Aurora Kagawa-Viviani for her mentorship and Paul Pestana for field and laboratory assistance. A special Mahalo (thank you) to Mahealani Botelho who co-designed the Pu'ulani Project, Nick Reppun, and all staff and caretakers of Kāko'o 'Ōiwi, the He'eia NERR, the volunteers who assisted in data collection, as well as the larger He'eia community. This is contributed paper CP-2021-11 of the Water Resources Research Center and publication JC-20-04 of the University of Hawai'i Sea Grant College Program, both at the University of Hawai'i at Mānoa, Honolulu, Hawai'i.

Conflicts of Interest: The authors declare no conflict of interest.

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