Maximizing Soil Carbon Sequestration: Assessing Procedural Barriers to Carbon Management in Cultivated Tropical Perennial Grass Systems

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Additional information is available at the end of the chapter

Abstract

The natural capacity of the terrestrial landscape to capture and store carbon from the atmosphere can be used in cultivated systems to maximize the climate change mitigation potential of agricultural regions. A combination of inherent soil carbon storage potential, conservation management, and rhizosphere inputs should be considered when making landscape-level decisions about agriculture if climate change mitigation is an important goal. However, the ability to accurately predict soil organic carbon accumulation following management change in the tropics is currently limited by the commonly available tools developed in more temperate systems, a gap that must be addressed locally in order to facilitate these types of landscape-level decisions. Here, we use a case study in Hawaii to demonstrate multiple approaches to measuring and simulating soil carbon changes after the implementation of zero-tillage cultivation of perennial grasses following more than a century of intensive sugarcane cultivation. We identify advancements needed to overcome the barriers to potential monitoring and projection protocols for soil carbon storage at our site and other similar sites.

Keywords: carbon sequestration, soil carbon, climate change mitigation, perennial grasses, zero-tillage

1. Introduction

As global demand for agriculture and bioenergy increases, so does the need to understand and predict not only the amount of food or energy that can be produced in large-scale agricultural systems, but also the environmental impacts associated with changes in agricultural land use and management. The effects of land-use change on soil carbon sequestration are poorly understood, particularly for novel bioenergy feedstocks. Maximization of carbon capture in agricultural systems through successive sequestration of photosynthetically fixed biomass carbon into soils for long-term storage has great potential to offset greenhouse gases in the atmosphere and mitigate climate change. However, the potential to sequester carbon in soil across cultivated landscapes for the purpose of climate change mitigation remains largely untapped, in part due to the complexity of soil carbon stabilization processes. In this chapter, we focus on a heterogeneous landscape in central Maui, a Hawaiian island, where sugarcane was intensively cultivated for over a century using preharvest burns and deep tillage. In 2011, a ratoon harvest system with zero-tillage management replaced sugarcane cultivation at select sites. Our objective was to identify current gaps in knowledge within the Maui system that diminish efforts toward accurate prediction of carbon capture and storage across this, and other similar landscapes in transition.

1.1. Factors controlling soil carbon stocks

1.1.1. Soil texture and mineralogy

Soil texture, particularly clay concentration, is commonly thought to predominantly influence soil organic carbon storage and therefore percent clay is commonly used as a modulator in simulation models like CENTURY [1] and Roth C [2] to help project carbon sequestration. However, other researchers investigating soil texture and soil carbon [3] found improved water holding capacity in silt-dominated soils and subsequently improved plant productivity, and thus suggest that silt may have greater effects on soil carbon sequestration than clays. Water holding capacity regulates oxygen supply and thus affects microbial decomposition [4]. In some tropical and subtropical soils, Fe-oxide cementations defy standard protocols for dispersion during texture determination and require specialized methodology to attain accurate clay concentrations that are not yet widely recognized in the literature [5]. Torn et al. [6] concluded that geological timescales were the strongest controlling factor of soil carbon change, but that was based on the stages of mineral weathering and the direct organomineral interactions that result in carbon stabilization. Specifically, the concentration of poorly or non-crystalline clay minerals can be a stronger factor controlling soil organic carbon storage than net primary productivity on millennial [6] and decadal [7] time scales. Although percent clay can be an adequate modulator for many systems, greater detail of information on soil texture and mineralogy often is needed in others such as systems of volcanic origin, arid regions, and subtropic/tropical ecosystems to improve model simulations of soil carbon accumulation.

1.1.2. Soil carbon stabilization, equilibrium and saturation

In reality, soil texture, mineralogy, climate, gross productivity and carbon allocation, land management, soil biota and their carbon use efficiency, and stabilization mechanisms such as

physical protection by aggregation and organomineral interactions act together to control soil carbon stocks. In the context of managing land to maximize soil carbon capture, the concepts of soil carbon stabilization, saturation, and equilibrium are critical because these processes dictate how quickly soil carbon will increase, the level of soil carbon reached, and whether the accumulated soil carbon stock will be resilient to future disturbance. In 2002 and 2004 reviews, Six et al. [8, 9] found (1) physiochemical soil characteristics control the maximum soil carbon stabilization capacity of soils; (2) microaggregates (<250 μm) are better at long-term soil carbon stabilization compared to macroaggregates (>250 μm); and (3) macroaggregate turnover is a strong driver of soil organic carbon stabilization across soil types and disturbance, with decreased macroaggregate turnover promoting increased long-term microaggregate stabilization. Soil aggregates, therefore, play multiple roles in soil carbon accumulation and should be protected and promoted with management decisions such as shifts to zero-tillage and minimal disturbance regimes.

Plant inputs also are an important factor in carbon stabilization, saturation, and equilibrium. In natural grassland systems of North America, litter mass losses contributed to soil carbon quickly at first through microbial decomposition, as well as more slowly through litter fragments moving into the mineral soil profile [10]. In tropical perennial grass systems, deep root inputs may have a greater influence on soil carbon accumulation than surface processes [11] because the aboveground biomass is removed. In cultivated landscapes, increases in organomineral complexes in the deeper soil profile under no tillage compared to conventional tillage led to a 16% increase of organic carbon [12]. A recent study of conservation agriculture in grasslands also found exchangeable calcium as the strongest single predictor of soil carbon in the top 10 cm [13], likely due to the positive effect of Ca^{2+} on soil aggregation in arid systems. Improving our assessment and understanding of soil carbon storage requires increasing our understanding of carbon stabilization while continuing to test and update conceptual models, especially those that span disciplines [14].

Advancements in technology as well as recent research findings support the move to mechanistic models of soil carbon processes. For example, Schmidt et al. [15] provide a succinct but wide-ranging source of reasoning behind the need for better observation-based and mechanistically driven conceptual frameworks. Lehmann and Kleber [16] argue for the need of soil science and interrelated disciplines to progress to a new model of soil organic matter and its interactions in the soil ecosystem. Their soil continuum model (SCM) is an attempt to reconcile three current conceptual models of the fate of organic debris in soils: (1) humification, or the classic belief in the synthesis of large recalcitrant molecules from decomposition products; (2) selective preservation, the assumption that preferential mineralization leaves intrinsically stable compounds; and (3) progressive decomposition, the concept of faunal and microbial size processing of plant inputs into smaller molecules. They argue that humic terminology should be relinquished; instead of suggesting that humic substances are a distinct category of organic matter in soils, they should be considered an analytical process of alkaline extracts. Further, recent advances in nuclear magnetic resonance (NMR) imaging, termed comprehensive multiphase NMR, has given one of the first analytical looks into the *in situ* soil-water interface and shows a complex mix of microbial and plant biopolymers with no evidence for cross-linked humic material [17]. The study also describes notable findings in relation to the soil-water interface that suggests carbon storage locations depend on the form of soil organic

carbon. These varied mechanisms of carbon stabilization could contribute to the disconnect between measured and modeled soil carbon as different carbon inputs may be mechanistically stored in different ways, thus creating nonlinearity between plant inputs and soil carbon sequestration.

1.1.3. Soil and crop management

Landscapes with soil properties that favorably control carbon stabilization could be preferentially transitioned into conservation management to improve carbon storage in certain cultivated agricultural systems. Conservation agriculture practices—including minimal tillage, residue management, and plant cover—affect the carbon cycle in agricultural systems, thereby altering ecosystem service provision [18]. In bioenergy production, where high primary productivity and maximum carbon capture in plant biomass are the primary goal, soil carbon sequestration can be a desirable secondary outcome with potent climate mitigation potential. Specifically, fast growing deep-rooted perennial grasses have the potential to input large amounts of carbon deep into the soil profile that can be protected by aggregate formation or organomineral interactions. A review of bioenergy crop "management swing potential" illustrates how management changes can swing the greenhouse gas emissions balance of agricultural production systems in positive or negative directions [19], which could offset negative carbon emissions from harvest and planting. Mutuo et al. [20] also discuss tropical agroforestry as another potential means to sequester carbon, finding large aboveground potential (60 Mg C/ha) but low belowground storage (25 Mg C/ha). However, they only investigated the top 20 cm of soil; investigation of the full soil profile may have revealed agroforestry increasing deeper, and potentially longer-term, soil carbon stocks. Anderson-Teixeira et al. [21] also found significant increases in belowground biomass of fast growing perennial crops compared to corn. Though soil carbon was not directly investigated in their study, it is expected that higher biomass in deeper depths likely increased deep soil carbon stocks compared to the typically shallow rooting of row crops like corn and soy. Getting carbon to deeper depths, minimizing its disturbance, and allowing physical and chemical protection mechanisms to remain intact are goals that conservation agriculture can help to achieve.

1.1.4. Soil bulk density and profile depth

When measuring soil carbon stocks, soil bulk density (i.e., mass per volume) and the whole soil profile (i.e., depth and development features) are critical to determining accurate total carbon stocks. Soil bulk density and profile depth have the most direct and simple effect on measured soil carbon stock, and more importantly accurately assessing the change in soil carbon stock postland use or management shift. In cultivated systems, determination of cumulative soil carbon using equivalent soil mass (ESM) methods accounts for changes in soil bulk density caused by management changes in compaction or tillage [22–24]. A recent study of a tropical forested system by Crow et al. [25] illustrates how different soil carbon measurement techniques (bulk density vs. ESM) can lead to conflicting carbon stock interpretations, especially in transitions between land management and crop type. By not accounting for compaction during land use change, average soil C change was overestimated by 14.9%, a difference that could have led to vastly different management decisions [25]. Though mineral soil

profiles can be several meters deep, many studies have only investigated surface soils even though change can be profound at depth [26]. More soil measured, even with lower carbon concentration at deeper depths, results in larger carbon stocks and, increasingly, deep soil sampling (to at least 1 m, if not more) are commonplace.

1.2. Simulation modeling and monitoring soil carbon change

In bioenergy feedstock production, where the environmental goal is to displace fossil fuels and promote carbon negative or neutral activity, maximizing carbon capture and sequestration in soils is important. As the societal costs of climate change increase, the economic value of carbon will also increase on a global scale [27, 28]. If carbon sequestration in a bioenergy feedstock production system can be fairly monetized, it could offset costs of establishing bioenergy production sites and help reduce uncertainty in an industry currently closely tied to fluctuating oil prices. Future management plans for soil carbon capture should include both environmental and economic sustainability factors.

The challenge of accurately measuring and projecting of carbon storage in agricultural systems increases as novel crops, large spatial scales, and heterogeneous soils and landscapes are utilized. Simulation modeling allows, with minimal on-site data collection, prediction of the potential of an area for climate mitigation or carbon monetization. Such models, calibrated to the specific processes controlling soil carbon accumulation at each site, can provide insight to land managers making landscape-level carbon decisions. With the precise tools, adaptive management plans may be made if monitored soil carbon stocks meet or miss simulated carbon potentials. Using simulation and projection modeling as a tool to investigate the effectiveness of carbon stock assessment methods (e.g., understanding the necessary sample quantities, spatial arrangements across a landscape, etc.) also helps determine the number and spatial distribution of samples needed to accurately quantify soil carbon stock change over time.

With subsequent advances in understanding of soil processes and representation in ecosystem and Earth system models, the potential exists to improve estimates of soil sequestration and projection models. Although many site-specific studies of soil organic carbon stocks have been completed, there remains uncertainty in the predominant soil processes that influence soil carbon storage and how these processes apply across heterogeneous landscapes of varying soil, temperature, rainfall, management, and other conditions to achieve carbon sequestration. Overly simplified models that consider only plant inputs as the driver of soil carbon are not accurate. Simple clay modifiers also are not effective in accurately modeling carbon storage for many soils, with noncrystalline mineral modifiers showing increased accuracy for some Andisol systems [29].

Several soil carbon models were developed for a specific cropping system, which makes it difficult to compare their performance against other models. Moreover, most models have not been fully parameterized and effectively tested for lack of adequate field measured SOC data, which is also crucial for the verification of model outputs. Soil subcomponent models that consider soil carbon dynamics and multiple pools, such as CENTURY, have shown to be reasonably good in simulating changes in SOC stocks, it is, however, important to note that

the C pool compartments are only conceptual, and have not been verified experimentally. Fundamentally, these models are based on outdated and oversimplified concepts of soil carbon formation. For example, static transfer rates among pools in the CENTURY model breaks down conceptually through time, and as demonstrated in this case study, have been shown empirically to be dynamic in certain systems. Moving toward more empirical models, resembling the SCM [16], that employ mechanisms like aggregate formation, organomineral interactions, and soil microbial biomass, among others, could help to better describe and model soil carbon cycles in the soil microbiome.

2. Ratoon harvest and zero-tillage management: a bioenergy case study in central Maui

Located in the central valley of Maui, Hawaii, between Haleakala and West Maui mountains, the Hawaiian Commercial & Sugar Company (HC&S) produced sugar from irrigated cane beginning in 1870 (**Figure 1**). The 36,000 acres of the HC&S plantation span large gradients of elevation, temperature, wind, and rain, which in turn generated high soil heterogeneity. From the start, HC&S preburned their sugarcane fields to reduce extraneous foliage and increase the percent sugar of collected material, which in turn improved the efficiency of their sugar extraction process. After the burn, cane stalks were mechanically ripped from the soil with their associated root bulb for processing; the fields underwent deep soil ripping (40 cm), and then were left barren until being replanted several weeks later. HC&S, as the last remaining large-scale agriculture company in the Hawaiian Islands, began transitioning in 2016 from sugarcane to diversified agriculture that will include large areas of perennial grasses for bioenergy feedstock and/or cattle forage. In this case study, the focus was on the heterogeneous landscape and identifying factors with predominant control on soil carbon stocks and accumulation following an experimental change from past intensive cultivation to ratoon harvest, zero-tillage management of tropical perennial grasses.
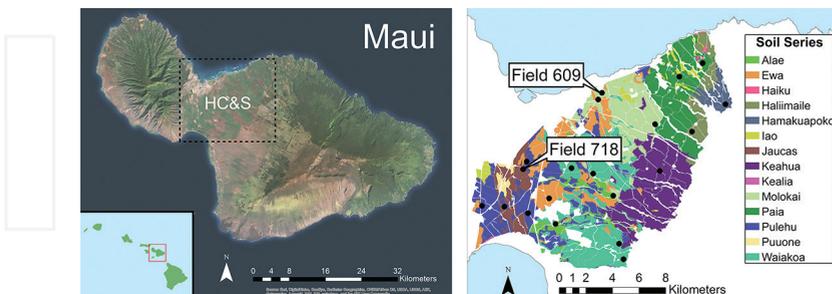

Figure 1. Maui with the main Hawaiian Islands inset (left) and Hawaiian Commercial & Sugar Company fields and associated soil series (right). Soil series data from: Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/. Accessed [07/30/2016].

2.1. Geospatial representation of soil parameters and baseline soil stocks

HC&S contains 14 soil series identified by the U.S. Soil Taxonomic system (**Figure 1**) that reflect heterogeneous soil properties across large areas of the plantation. As a first step to improve model simulations of soil carbon accumulation at the plantation scale, primary soils data (including GPS locations, horizon depths, bulk density, soil texture, pH, total carbon and nitrogen concentration, and organic carbon concentration) were collected for 20 map units across HC&S. These 20 map units represent 7 soil orders, 10 soil series, and ~77% of total plantation area. Data from these 20 fields also provide a baseline of soil carbon stocks under more than a century of intensive cultivation of sugarcane.

Raster interpolation was used to investigate geospatial relationships between soil organic carbon and potential factors that affect soil carbon sequestration. The field data were analyzed in ESRI ArcGIS using ordinary spherical kriging from the 3D analyst toolbox. Geospatial patterns emerged in soil texture data in both the percent sand and clay (**Figure 2**) but none were apparent for percent silt, which was approximately 50% for most of the soils tested (data not shown). The wetter, higher elevations going up Haleakala Mountain showed high levels of clay, while the west side of the plantation had more sand dominant soils. Standard protocols were used for the textural classification and therefore the percent clay may be underestimated and percent sand may be overestimated for some of the soils; however, these observation are consistent with greater clay development in wetter, upland soils and sandier clays in low lying areas that were subject to sea-level rise. pH did not show clear trends in space (results not shown), although we did find that a majority of the soils across the plantation were very basic (pH 7–8), with the most acidic areas slightly under pH 6. This is likely due to soil parent material (e.g., basic igneous rock in the Keahua series and calcareous sand deposits in the Jaucas series) in parts of the plantation and high application rates of lime as needed for productivity throughout.
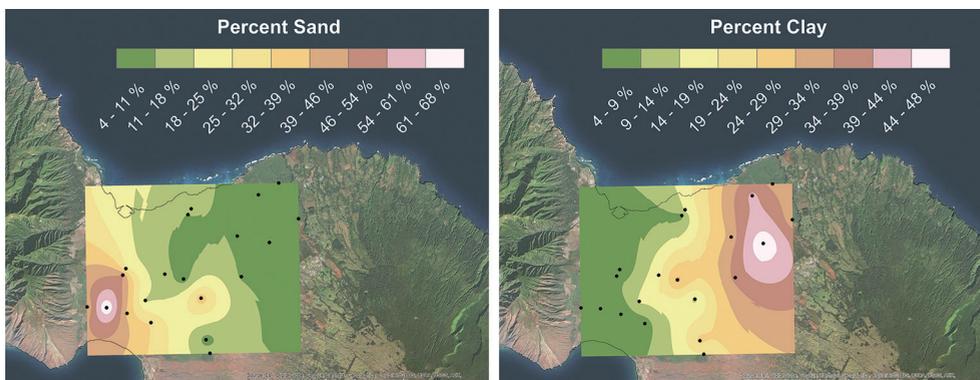

Figure 2. Simple spherical kriging of texture data gathered from 20 fields across the HC&S plantation: percent sand (left) and percent clay (right). Interesting geospatial patterns of sand and clay appear but do not well explain the patterns found in organic carbon stocks across HC&S.

The equivalent soil mass (ESM) method as described in the introduction (Section 1.1.4) was used to calculate a carbon stock for each of the 20 fields and the same methods described above were used to generate a geospatial representation of baseline soil carbon stock for the plantation (**Figure 3**). Four arbitrary cumulative soil reference masses were chosen based on the sampling scheme and typical cumulative soil masses found by the ESM method in the 20 fields data. The ESM reference masses chosen were 2500, 5000, 7500, and 10,000 Mg/ha, with each ESM reference mass interpolated similarly to the texture data using ordinary spherical kriging in ArcGIS. These masses roughly equate to a 0.6 m depth, although the exact depth is different for every soil. There were no strong geospatial patterns for soil carbon stock in the shallowest soils (ESM 2500), with spatial patterns emerging only after the inclusion of the deeper soil profile. Long periods of deep tillage and a monoculture cropping system with similar amounts of litter and shallow root inputs are possible causes for the lack of geospatial difference in the surface soil carbon stocks. However, the final pattern that emerged in ESM 10,000, where higher carbon stocks appear to be in wetter northeastern fields along the windward side of Haleakala and western fields toward the West Maui Mountains, does not have a simple explanation.
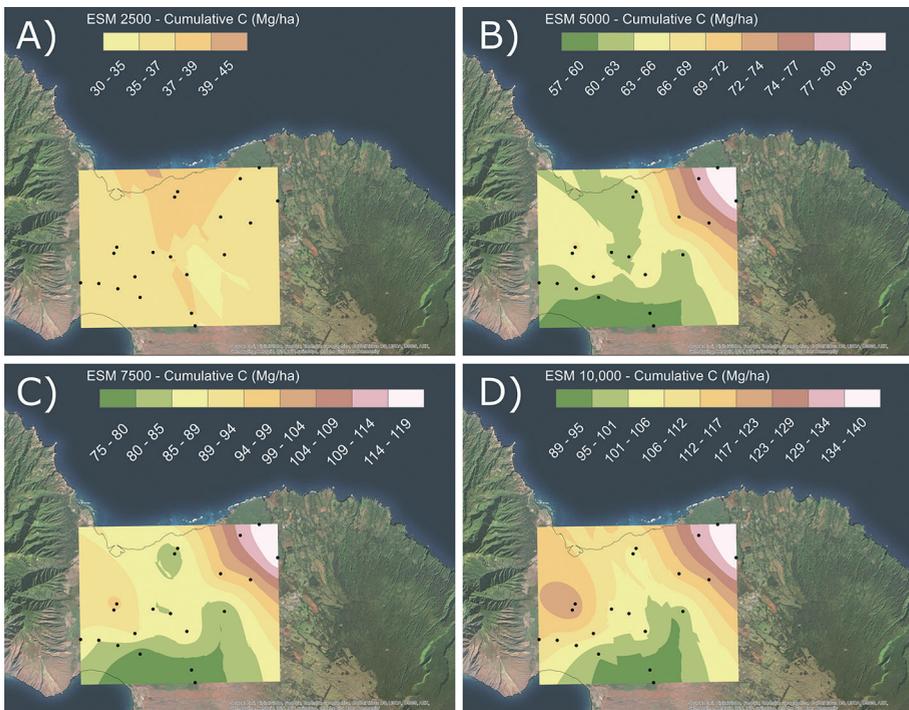

Figure 3. Simple spherical kriging done in ArcGIS estimates the distribution of baseline carbon across the HC&S plantation at four ESM reference masses: (A) 2500 Mg/ha; (B) 5000 Mg/ha; (C) 7500 Mg/ha; (D) 10,000 Mg/ha. Carbon stocks are represented on differing scale bars to illustrate changes in geospatial patterns as more of the depth profile is considered. ESM 10,000 (full profile) shows highest carbon accumulation toward the West Maui Mountains and northeast toward Haleakala Mountain, possibly following a climatic gradient of rainfall and soil weathering.

Soil texture and pH did not align overall with the patterns in soil organic carbon (**Figure 3**), although higher clay in the northeast areas of HC&S does generally align with higher carbon storage. Some of the higher clay areas are also known to have volcanic ash deposits and the soils have andic properties (e.g., Haliimaile and Hamakuapoko series in the northeast) or are classified as Andisols (e.g., Alae series spread throughout in small areas). Poorly or noncrystalline minerals derive from volcanic ash deposits, thereby confounding the influences of clay concentration and mineralogy. Future work will include exploring modified methods to quantify various forms of iron and aluminum oxides as possible drivers of organomineral sorption, water stable aggregates as a representation of physical protection, and comparison of climate data like temperature and rainfall as factors controlling clay weathering. Nonetheless, this is the first geospatial look at soil carbon stocks at this location and represents an initial attempt at soil carbon stock measurement and monitoring in this highly cultivated tropical perennial grass system. Higher sampling density of the plantation will likely be needed to corroborate these potential geospatial patterns.

2.2. Measured soil carbon stocks

2.2.1. Validation of geospatial interpolation of baseline values

Experimental plots were established at multiple locations across the plantation to investigate aspects of potential bioenergy production including: (a) growth characteristics of multiple novel feedstock crops, (b) water use efficiency and stress management, (c) the effects of elevation/wind/rain gradients, (d) emissions of greenhouse gases from soils, and (e) soil carbon sequestration based on management and soil properties. Soil carbon stock changes over time were measured at each site from baseline to year 3 postmanagement change. This case study focuses on soil carbon stocks at two-field plots established in the HC&S commercial fields 718 (Pulehu series; fine-loamy, mixed, semiactive, isohyperthermic Cumulic Haplustoll) and 609 (Molokai series; very-fine, kaolinitic, isohyperthermic, Typic Eutrotorrox) (**Figure 1**) to validate the geospatial interpolation method for determining baseline carbon stocks. Comparison of the baseline cumulative soil carbon data collected at field 718 (~126 Mg/ha at ESM 10,000) and 609 (~111 Mg/ha at ESM 10,000) (**Figure 4**) shows fairly close agreement with the plantation-practice baseline interpolation of the 20 field's dataset that indicate 117–123 Mg/ha and 101–106 Mg/ha of cumulative carbon at fields 718 and 609, respectively (**Figure 3d**). However, further comparison of both pit sampling and core sampling at identical locations will be needed to confirm agreement between the two ESM calculations.

2.2.2. Change over time

Focusing specifically on field 718 and a high performing hybrid energy cane (*Saccharum Officinarum* × *Saccharum Robustum*) feedstock, soil carbon stocks after conversion from intensive sugarcane cultivation to annual ratoon harvested energy cane exhibited substantial sequestration during the first 3 years (**Figure 5**). For this comparison, ESM data was calculated from soil cores dug using hand augers, with samples divided into 20 cm soil depth increments to 1.2 m. Within the collected soil profile, as represented in the ESM of 18,000 Mg/ha (roughly equivalent to 1 m depth, but all cores were different), high levels of cumulative
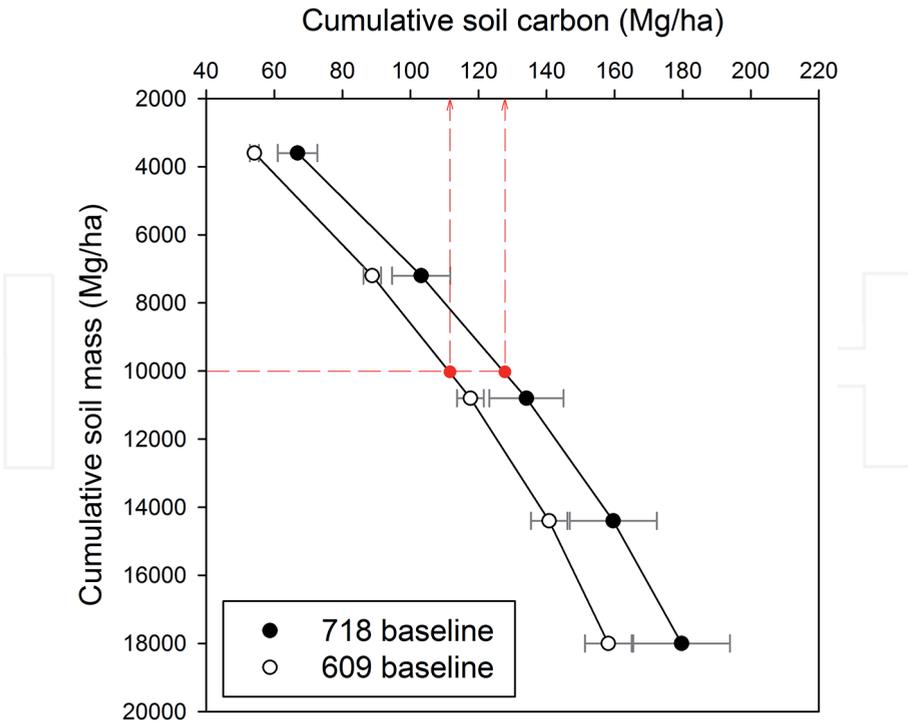
Figure 4. ESM data from baseline measurements of fields 718 and 609 are depicted with red line representing the 10,000 Mg/ha soil reference mass. When cumulative carbon from fields 718 and 609 are compared to the 20 field's interpolation, decent agreement between spatial model and measured ESM values are found.

carbon sequestration are apparent under conservation agriculture. It is known that following the shift from intensive cultivation to conservation practice, initial soil carbon accumulation rates will be high and decrease over time as a system saturates and reaches a new equilibrium. In this case study, the average annual cumulative soil carbon over the first 3 years was calcu-lated as an estimate of soil carbon sequestration potential after the implementation of conser-vation agriculture in the surface soils and the deepest soil mass depth (ESM 3600 and 18,000; **Figure 5**). Net carbon sequestration is expected to continue at decreasing rates if conservation agriculture is maintained, but, in the first 3 years, the mean soil carbon sequestration at field 718 was 2.34 ± 1.03 Mg C/ha/yr in the surface soils and 12.75 ± 2.76 Mg C/ha/yr in the deeper soil profile over the 3-year experiment. These gains are in the range of recently reported rates of 3.9 Mg C/ha/yr in the surface soils of a tropical Napier grass system [30] and 5.0 Mg C/ha/yr in the top 1 m of a subtropical sorghum study [31]. Fluctuations in soil carbon stock occurred during the transition to conservation agriculture in this tropical perennial system. Rapid carbon sequestration in the first 2 years from baseline while the crops were establishing the below ground system and rhizopshere, with a slight reduction in carbon storage in year 3 (**Figure 5**). These data may indicate increasing but also naturally oscillating soil carbon stocks under improved soil management.
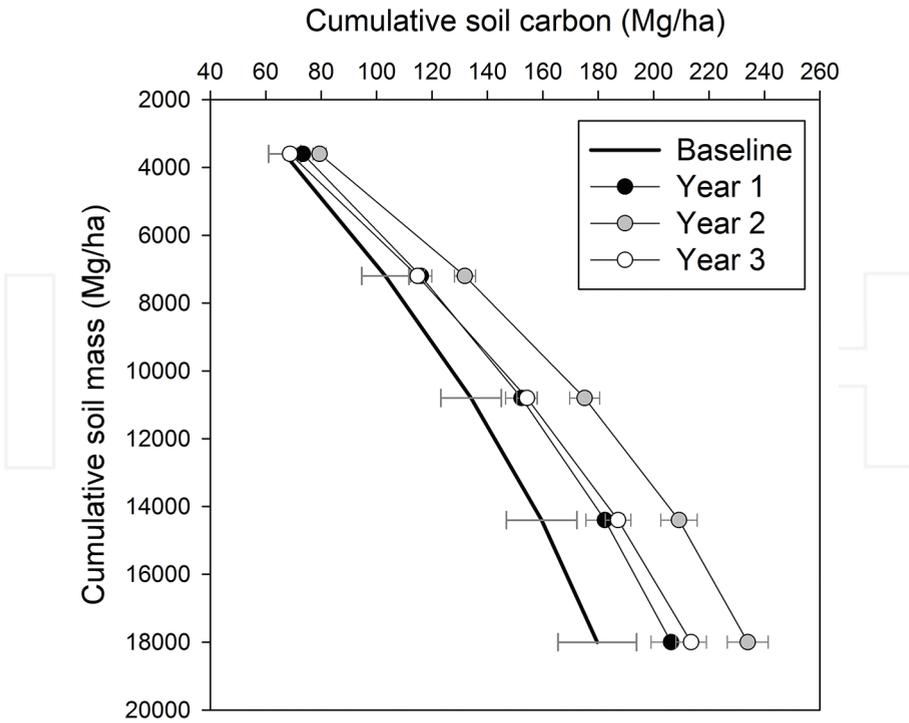
Figure 5. Cumulative soil carbon as measured by equivalent soil mass (ESM) methods at field 718 under ratoon harvest energy cane and zero-tillage. Increases in cumulative carbon at 5 ESM reference masses are shown by a shifting to the right from baseline. An unexplained drop in year 3, especially in the lowest reference mass, may show large natural fluctuation in carbon stocks.

To scale-up carbon storage to other areas of the plantation, we compared soil properties of the Pulehu series found at field 718 with nearby soils (**Table 1**). Specifically, the Paia, Waiakoa, and Ewa soil series (Mollisols) were chosen as adjacent areas with similar soil properties to field 718. However, important differences in detailed soil properties (e.g., percent clay) among the four soil series, suggest that only the plantation area under the original Pulehu soil should be used for scaling up (**Table 1**). Simple extrapolation of surface soil and deep soil carbon sequestration potentials found at field 718 (2.34 ± 1.03 and 12.75 ± 2.76 Mg C/ha/yr, respectively) across areas of the Pulehu series (1763 ha, representing ~11% of the HC&S plantation) equates to a prospective soil carbon sequestration potential of 4.1 ± 1.8 Gg C/yr that could be taken from the atmosphere and stored in similar surface soils compared to 22.5 ± 4.9 Gg C/yr that could be stored throughout the deeper soil profile in the first 3 years of transition to conservation agriculture. However, these initial carbon sequestration rates are expected to decrease with time as the soil's potential for carbon storage is saturated. Geospatial differences in carbon sequestration due to soil and environmental heterogeneity across the plantation also make these estimates rather uncertain, but these findings clearly indicate that deep (≥1 m) carbon sampling is important when considering landscape level soil carbon stocks as inclusion of the deep soil profile increased carbon stocks several fold.

Properties: Sites sampled	Pulehu $n = 4$	Ewa $n = 2$	Paia $n = 2$	Waiakoa $n = 4$
taxonomy (NRCS)[1]	Cumulic haplustolls	Aridic haplustolls	Torroxic haplustollus	Torroxic haplustolls
Parent material[1]	Igneous alluvium	Basaltic alluvium	Igneous residuum	Igneous residuum
Clay mineral type[1]	Mixed	Kaolinite	Iron oxide	Kaolinite
Bulk density (g/cm³)	1.27 ± 0.06	1.19 ± 0.15	1.15 ± 0.03	1.32 ± 0.07
Soil porosity (%)	51.99	55.09	56.60	50.2
Texture	Clay loam	Silty clay loam	Silty clay	Silty clay loam
Clay (%)	5.85 ± 1.16	11.22 ± 3.35	35.90 ± 3.78	22.64 ± 3.10
Silt (%)	51.91 ± 9.96	75.15 ± 6.5	57.53 ± 4.97	66.61 ± 1.07
Sand (%)	42.24 ± 9.84	13.66 ± 3.14	6.58 ± 1.20	10.75 ± 2.33
Soil pH	7.45 ± 0.28	7.20 ± 0.2	7.60 ± 0.13	6.87 ± 0.53
SOC (%)	1.44 ± 0.16	1.99 ± 0.78	1.72 ± 0.20	1.28 ± 0.12
Total nitrogen (%)	0.12 ± 0.01	0.13 ± 0.03	0.17 ± 0.03	0.1 ± 0.01
C/N (using organic C)	12.43	15.27	10.12	12.30

[1]Data taken from NRCS Soilweb database, all other data collected during 20 field sampling using NRCS soil sampling protocols.

Table 1. Descriptive data of similar Mollisol soils series in Hawaii at HC&S (sampled during 20 fields experiment).

2.3. Model comparison: ALMANAC versus three pool transfer model

Finally, in an effort to project past the 3 years of data and to better understand the mechanisms that control how carbon is entering and moving through the soil system, we performed a physical separation of soil pools (i.e., density fractionation with sonication to disrupt an aggregated fraction) and subsequent simulation and projection model in SoilR [32] using the surface soils of field 718 and the ESM 3600 carbon accumulation values. The fractionation method used was based on Golchin et al. [33], in which sodium polytungstate (SPT) was used to increase the extraction density with free light, occluded light, and dense fractions sequentially separated by 1.6 g/L SPT solution. The free light fraction, which represents fresh plant inputs like roots and litter, was separated from the soil through light agitation by hand followed by centrifugation and aspiration. To obtain the occluded light fraction, which represents carbon that has been physically protected by soil aggregation, the soil slurry was sonicated with 400 kJ/mL to disrupt aggregates, and the released occluded carbon was captured by centrifugation and aspiration. Finally, the dense fraction was quantified as the soil that remained. The weights of recovered fractions and the percent carbon of each fraction were measured and then used to calculate the distribution of carbon between the pools. Strong decreases in litter/root inputs and aggregate protected carbon, as represented by the free light and occluded light fractions, respectively, were found. However, large increases of carbon in the mineral-rich dense fraction drove increases in carbon stocks in the surface soils (**Figure 6**). As this data-driven model is only a representation of surface soils, it will be important to
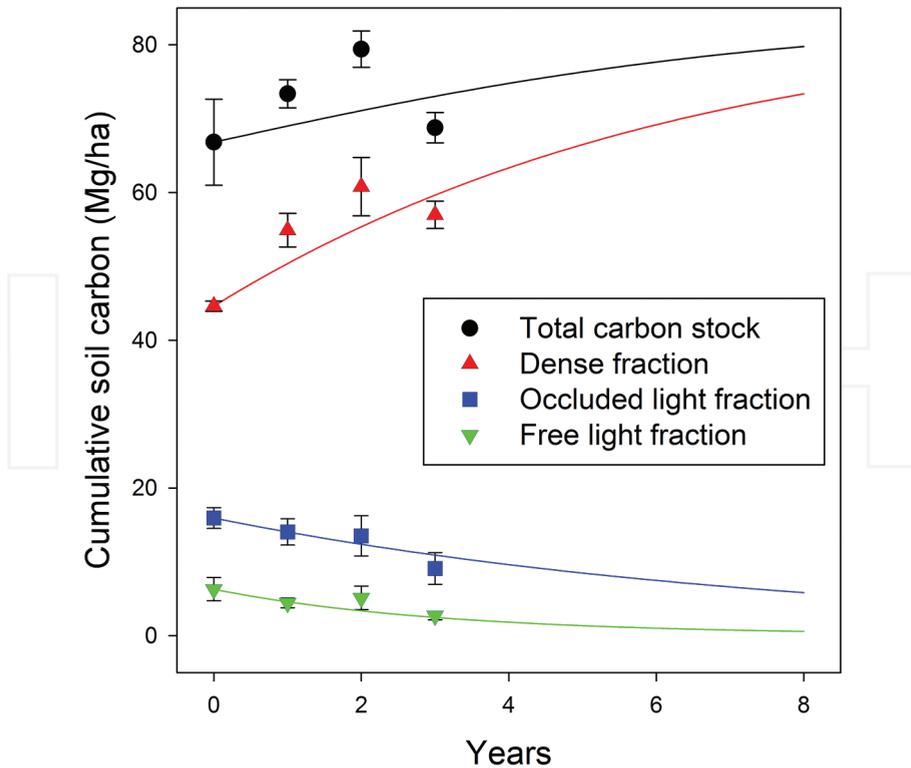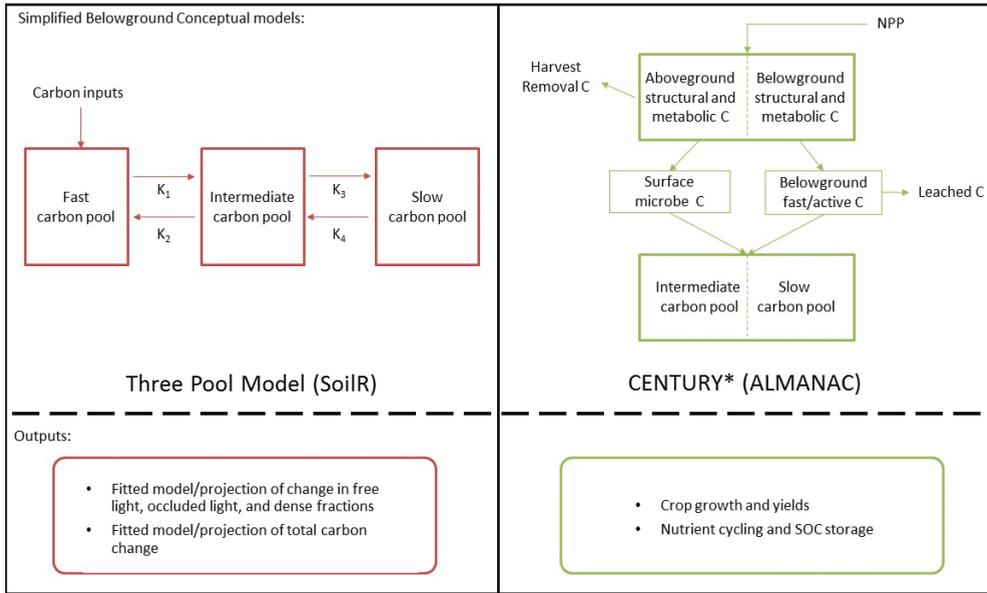
Figure 6. Three-pool model completed in SoilR (R project package, [32]) using density fractionation and measured ESM soil stock data from field 718 under ratoon harvest energy cane and zero-tillage. An ESM reference mass of 3600, which represents the shallowest mass soil depth was used for C stocks (**Figure 5**). Pool fraction data was determined from 0 to 20 cm depth samples (same cores ESM carbon stocks were calculated from).

further investigate the lower soil mass depths to see if mineral-driven carbon sorption is prevalent throughout the depth profile. A model of the entire soil profile (ESM 18,000) will be completed to project forward changes in total carbon stock as more of the depth profile is density fractionated.

A second model simulation of carbon storage was completed using the ALMANAC soft-ware [34]. As a crop model, ALMANAC uses a broad range of inputs to model soil carbon compared to SoilR (**Figure 7**). In the ALAMANC model, based on the field experiment and expected future management, the plough layer was set to 20 cm, energy cane was ratooned for 4 years and was then killed, ripped, harrowed, and replanted. These operations were based on farmer practice of periodically ploughing-back their conservation-tilled lands to alleviate problems of drainage, pests, and soil compaction [35]. The model was then run for a total of 25 years, with 10 years of preruns to stabilize model input variables prior to 2011. From 2011, the cumulative soil carbon of the surface soil (ESM 3600) and full soil profile (ESM 18,000) at field 718 were projected out to 2025 (**Figure 8**). Projected soil carbon stocks from the surface

Figure 7. Conceptual representations of the processes involved in both the three pool SoilR model and the ALMANAC crop model. The empirical SoilR model requires soil carbon and density fractionation data to estimate fluxes between soil carbon pools, while the ALMANAC process model focuses on soil, crop, management, and weather data to estimate soil carbon stocks using the CENTURY soil carbon submodel for belowground carbon estimates. Comparing these two vastly different approaches helps to identify areas of improvement for carbon stock modeling in the future.
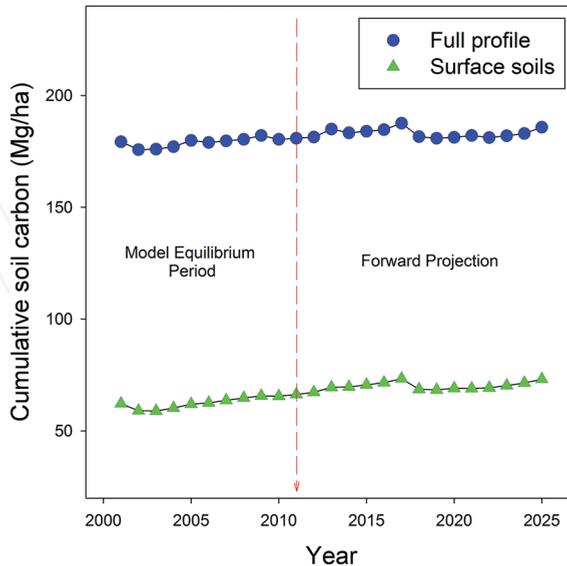

Figure 8. ALMANAC projection of surface soils (ESM 3600) and full soil profile (ESM 18,000). Ten years (2001–2010) were completed as a model equilibrium period before forward projection from 2011 for 15 further years.

soils for both the three pool SoilR model and the ALMANAC model were then compared to the measured data (**Figure 9**).

To compare modeled outputs with averaged yearly soil carbon increase data, the year 5 modeled outputs from SoilR and ALMANAC were compared and scaled across the Pulehu soil series in the same manner as the measured data. Increases of 1.9 and 1.1 Mg C/ha/yr were found in the surface soils by the SoilR and ALAMANAC models, respectively. Scaling these values with the same area of similar Pulehu soils (1763 ha) shows a soil carbon sequestration estimate of 3.3 and 1.9 Gg C/yr for SoilR and ALAMANC models, respectively. This estimate covers approximately 11% of the HC&S plantation area. As the SoilR model was of the surface soil only, it will be important to repeat this exercise with the deeper soil profile, especially considering that surface soils have shown the least differences under conservation agriculture. In contrast, the ALMANAC model was projected forward from a carbon baseline derived from the full depth profile, with year 5 showing an increase of only 0.8 Mg C/ha/yr when the deep soil profile is considered. Scaling up the ALMANAC output at year 5 gave a comparatively low value of 1.3 Gg C/yr sequestration potential across Mollisol soils at HC&S. Importantly, comparison of measured data and multiple models allows us to test different assumptions used, with further data collection and analysis expected to help improve and
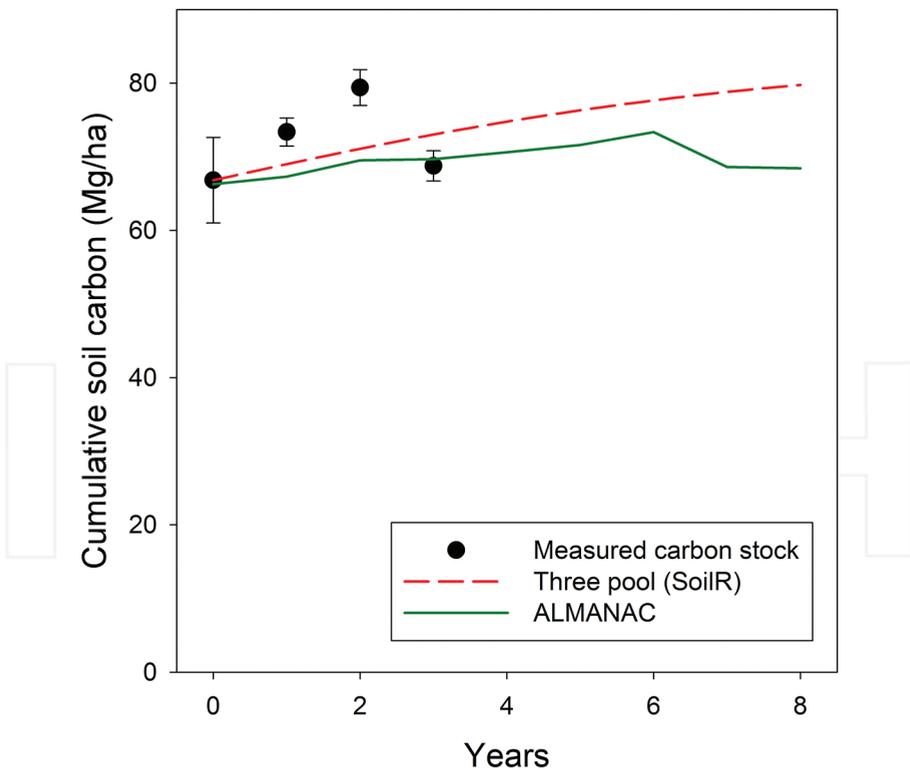

Figure 9. Two models (ALMANAC and SoilR) projected forward from surface soil (ESM 3600) for 8 years compared to measured data.

refine not only the model end products, but also the underlying assumptions that are relied on to understand soil carbon sequestration and storage in the tropics.

3. Conclusion

Carbon storage potential on the plantation scale in productive tropical cultivated systems is high when transitioning into conservation agriculture, especially when the deep soil profile is considered. Deep soil carbon increases, attributable to fast growing deep-rooted perennial grasses, led to a high belowground carbon sequestration potential (4.1 ± 1.8 and 22.5 ± 4.9 Gg C/yr in the surface and deep soils, respectively) if the average yearly increase of soil carbon at field 718 is generalized across similar Pulehu soils at the HC&S plantation. Taking modeled soil carbon stocks in the surface soils and scaling similarly gave 3.3 Gg C/yr from the SoilR model and 1.9 Gg C/yr from the ALMANAC model. However, much lower estimates were found when the deep soils were projected forward (only 1.3 Gg C/yr estimated by the ALMANAC model). As SoilR requires more fraction data from the deeper profile, it will be interesting to see if SoilR consistently has a greater estimate and ALMANAC a lower estimate of soil carbon sequestration. Nonetheless, these results point to a large potential for carbon storage through conversion to conservation agriculture; if monetized, these carbon storage potentials could be a huge prospective boon to the value of HC&S as a bioenergy site with proper soil and harvest management.

As indicated by the density fractionation results from commercial field 718, soil carbon storage is likely driven by mineral sorption in our system. However, there is need to refine our understanding of mineral changes across such a heterogeneous landscape, with continued density fractionation and iron/aluminum oxide measurements expected to better explain variations in soil carbon storage across HC&S. The estimated sequestration potentials will also need further improvement through comparison of our other field trials to determine if geospatial variations in soil texture and mineralogy will affect total carbon sequestration potentials across this heterogeneous landscape. Through continued and more detailed mineralogy and the addition of detailed climate, net primary productivity, and belowground biomass data, we expect to uncover relationships between the many factors controlling soil carbon sequestration in this system. Determination of better metrics and relationships of soil properties to carbon sequestration across the heterogeneous landscape of HC&S will enable more accurate projection of carbon sequestration potentials in Hawaii and other similar tropical perennial systems.

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