Final Report
State of Hawaiʻi Office of Planning and Sustainable Development

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Purpose

The original purpose of this contract was the development of data resources required to generate a baseline and short- and long-term benchmarks for increasing greenhouse gas (GHG) sequestration, soil health, and yields in natural and working lands (e.g., pasture, agriculture, agroforests) in Hawaiʻi's agricultural forestry and other land uses (AFOLU) sector.

Scope of Work

The original scope of work developed by the State of Hawaiʻi's Office of Planning and Sustainable Development was that the contractor, Joshua Silva, would collaborate with Susan E. Crow, Ph.D., in the collation of available data and collection of additional data resources for natural and working lands to provide the scientific basis for initialization of a decision support and planning tool and to establish benchmarks for critical indicators of change in GHG sequestration from the AFOLU sector and best management practices to support soil health, climate change mitigation, and yield in Hawaiʻi.

a. Compilation of available datasets for soil carbon, and other attributes, inventory in Hawaiʻi for working lands through Natural Resources Conservation Service (NRCS), National Cooperative Soil Survey (NCSS) datamart and Rapid Carbon Assessment (RaCA) downloads, acquisition of other large datasets from Hawaiʻi and county watershed partnerships, researchers and agencies, and literature review
b. Collection of soil health, yield, and GHG sequestration data from a network of productive lands, farmers, and ongoing trials as required for initialization of the Colorado State University and NRCS decision support and planning tools and verification of the outcome projected for adaptive management scenarios.

Compilations of Available Data

Compilations of available data for soil GHG flux, soil carbon (C) stocks, and cross- sectoral public GIS layers for land use and collection of novel soil health data are available at the following permanent links in ScholarSpace, the University of Hawaiʻi's open-access digital repository.

Hawaiʻi Greenhouse Gas Database http://hdl.handle.net/10125/76002
Crow, S., & Rivera-Zayas, J. (2021, July 19). Hawaii greenhouse gas emissions database. https://doi.org/10.17605/OSF.IO/JPR7Q

Hawai‘i Soil Carbon Database http://hdl.handle.net/10125/76001
Citation: Crow, S., Rivera-Zayas, J., & Vizka, E. (2021, July 19). Hawaii Soil Carbon database. https://doi.org/10.17605/OSF.IO/HMTV6
Hawai‘i Land cover Maps http://hdl.handle.net/10125/76000
Hawai‘i Gaps in Land Cover Maps http://hdl.handle.net/10125/75999
Hawai‘i TMK Conflict Maps http://hdl.handle.net/10125/75997
Hawai‘i Soil Health Dataset http://hdl.handle.net/10125/75998

This report was commissioned by the State of Hawai‘i on behalf of the Greenhouse Gas Sequestration Task Force and the Office of Planning and Sustainable Development, using funds provided by Act 15, Session Laws of Hawai‘i 2018, now codified as Hawai‘i Revised Statutes §225P-4. As requested by the State of Hawai‘i's Office of Planning and Sustainable Development, this report provides an index of references included in the data compilations found at the links, and discusses the known and studied sources of soil GHG flux and C storage and sequestration of Hawai‘i's natural and working lands. The discussion is based on available data from online research, journal articles, agency reports, and unpublished scientific data from reputable sources. This report also discusses the soil health data collected as part of this contract in comparison to our current state of knowledge of soil health across the natural and working lands of Hawai‘i. Additional assessments are provided that summarize the currently available data and highlight unique aspects of Hawai‘i's soils and ecosystems as well as knowledge gaps that persist and are barriers to an accurate GHG emission benchmark and baseline assessment for Hawai‘i's natural and working lands that comprise the AFOLU sector.

Glossary of Terms

Andisol	Soil order formed in volcanic ash; often characterized by high organic matter, fertility, and poorly or non-crystalline minerals, and low bulk density
Aridisol	Soil order characteristic of arid regions and typically compromise saline and alkaline soils with low organic matter
C_3 plants	C_3 plants do not have photosynthetic adaptations to reduce photorespiration, includes 85% of the plant species, including rice, wheat, and soybean
C_4 plants	C_4 plants avoid photorespiration, are resistant to heat and drought, and have higher water use efficiency. Includes tropical grasses such as maize, sugarcane, and sorghum
Carbon sequestration	The process of removing carbon dioxide (CO_2) from the atmosphere and depositing it in a reservoir
Cultivar	A plant variety that has been produced in cultivation by selective breeding
Denitrification	The process by which combined nitrogen is reduced to gaseous end products (nitric oxide (NO) and nitrous oxide (N_2O))
Effluent	Liquid waste or sewage
Greenhouse gas sequestration	The process of removing greenhouse gases from the atmosphere and depositing it in a reservoir. Use of this broader phrase is to include non-carbon compound gases such as: Nitrous Oxide (N_2O), Sulfur Hexafluoride (SF_6), and Nitrogen Trifluoride (NF_3) which also have High Global warming Potential “High GWP gases”
Inceptisol	Soil order containing freely draining soils in which the formation of distinct horizons is not advanced
Lignin	A complex organic polymer deposited in the cell walls some plants making them rigid and woody
Mesic	Moderate or well-balance supply of moisture
Microbiome	The microorganisms in a particular environment
Mollisol	Soil order formed in semi-arid to semi-humid areas; characterized by deep, high organic matter, and nutrient-enriched surface soil with a typical depth of 60 to 80 cm in depth
Nitrification	Is a microbial process by which reduced nitrogen compounds are sequentially oxidized to nitrite and nitrate

Oxisol	Soil order containing highly weathered, low fertility tropical sois, often composed of stable iron oxides and kaolinite minerals
Perennial plants	Plants that live more than two years
Ratoon harvest system	The agricultural practice of harvesting a monocot crop by cutting most of the above-ground portion but leaving the roots and the growing pieces to allow the plant to recover and produce a fresh crop in the next season
Rhizosphere	The region of the soil in the vicinity of plant roots in which the chemistry and microbiology is influenced by root growth, respiration, and nutrient exchange
Soil efflux	The rate at which soil C is released into the atmosphere through autotrophic and heterotrophic respiration
Soil flux	The rate (amount over a certain period of time) at which sources and sink of gases move within the soil
Ultisols	Soil order characterized by strongly leached, acidic (sub)tropical soils with low fertility

Acronyms List

AFOLU	Agricultural forestry and other land uses
ALUB	Agricultural land use baseline
ALUM	Agricultural land use maps
B glu.am	B-glucosaminidase
B gluc	B-glucosidase
BD	Bulk density
C	Carbon
C-CAP	Coast change analysis program land cover
CAH	Carbon Assessment of Hawai‘i
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DEMs	Digital elevation models
DOC:DON	Ratio of dissolved organic carbon to dissolved organic nitrogen
floodpl	Floodplain
g	Gram
GHG	Greenhouse gas
ha	Hectare
HAC	High activity clays
HI-GAP	Gap analysis program land cover
HSH	Hawaii Soil Health
HWEC	Hot water extractable carbon
IAL	Important agricultural lands
IPCC	Intergovernmental panel on climate change
kg	Kilogram
LAC	Low activity clays
LF	Landfire vegetation
LiDAR	Light Detection and Ranging
LSB	Land Study Bureau

LU	Land use
LULC	Land use cover
m^2	Square meter
mega-WSA	Mega-size class water stable aggregates
Mg	Megagrams
N	Nitrogen
N_2O	Nitrous oxide
NCSS	National cooperative soil survey
NERR	National estuarine research reserve
NRCS	Natural resources conservation service
OrgCrop	Organic cropland
P	Phosphorus
PMN	Potentially mineralizable nitrogen
PNCM	Poorly and non-crystalline minerals
ProFor	Protected forest
RaCA	Rapid carbon assessment
SOC	Soil organic carbon
UPIAL	Unmanaged previously intensive agricultural lands

Executive Summary

Data resources additional to national-level surveys and inventories are required to generate a baseline and short- and long-term benchmarks for increasing greenhouse gas (GHG) sequestration, soil health, and yields in natural and working lands (e.g., pasture, agriculture, agroforests) in Hawai‘i's agricultural forestry and other land uses (AFOLU) sector. Widely applied assumptions, equations and models pertaining to the amount (stocks), fluxes (rate of emission or drawdown), and expected change (as a result of land use or management) are insufficient for Hawai‘i's unique soils, climates, and ecosystems. This report delivers compilations of site-specific GHG flux and soil carbon (C) measurements along with meta-data that describe location, year of sampling, land use/management, and other descriptions in order to support the development of Hawai‘i-specific decision support tools and opportunity assessment. Summaries of key land use types and management are provided and insights into a few key challenges and opportunities in the AFOLU sector are presented. More than 50 articles for GHG emissions, sequestration, and soil C data were found for different land use types and management systems in Hawai‘i, highlighting the potential of certain practices such as bioenergy crops and organic residues in building soil carbon stocks and reducing GHG emissions.

Key takehomes for natural and working lands in Hawai‘i

- Natural and working lands are critical to Hawai‘i's climate readiness. Yet complex, and potentially competing, factors across conservation, food, energy, and urbanization within the AFOLU sector affect decisions that ultimately impact climate outcomes.
- Substantial local-scale data resources for GHG and soil C exist across Hawai‘i that can be harnessed to improve inventories and assessments. The role of grazed pastures and livestock systems in climate change mitigation has been overlooked in Hawai‘i and assessments rely heavily on assumptions that may not be valid for Hawai‘i.
- A cross-sectoral GIS layer that weaves natural and working lands and urban areas is required to build jurisdictional optimization tools for climate actions and power data visualizations that are critical to communicating needs and facilitating discussions.
- The Hawai‘i Soil Health Tool is a web-based portal for soil health information and requesting soil health testing as part of ongoing research projects that will help set baselines and benchmarks for Hawai‘i. Public services for soil health testing are imperative for implementing programs that support legislative mandates to improve soil health in natural and working lands. All landscapes have the potential to improve soil health and their stewards should be supported to do so.
- Investment is required to build data resources into decision support tools for Hawai‘i's unique soils, systems, and communities that accurately assess reasonable benchmarks and baselines. Only then, can opportunity assessments identify clear pathways to achieve multiple climate goals including mitigation, adaption, and resilience.

1. Greenhouse gas flux

Overview. The primary GHG emissions of concern in this report are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). National and State GHG inventory relies on 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories and the 2019 Refinement - Tier 1 equations (most basic method with least complexity and least accuracy) are used for estimating emissions for each gas and are not systematically verified or validated with Hawaiʻi-based measurements. Sources of GHG emissions in AFOLU are known to be: livestock, fertilizers, natural cycles, water fluctuations. Hawaiʻi's soils and ecosystems are so different from others, that local or regional knowledge must be accessed to improve inventories and modeling tools that are used for decision support and policy. The following data compilation is of the known available site-specific measurements made in Hawaiʻi.

Data compilation.

Table 1. Index of known references for greenhouse gas emissions data in Hawaiʻi's natural and working lands.

Natural or Working Land Sector	**Management systems**	**Management or Land cover**	**References**
Cropland	Crops Intensive sugarcane cultivation	Conventional tillage and fertilizer management	Matson et al., 1996; Tran and Yanagida, 2019; Zachariassen et al., 1996; Pawlowski et al., 2017 and 2018
	Tropical perennial grasses	Zero tillage, sugarcane and related bioenergy feedstocks, e.g., energycane, napier grass (*Cenchrus purpureum)*,Guinea grass (*Megathyrsus maximus)* and others.	Pawlowski et al., 2017 and 2018; Meulemans, 2016; Crow et al., unpublished; Sumiyoshi et al., 2016
	Biochar	Biochar	Meulemans, 2016; Biegert, 2015
	Organic	Organic amendments	Meulemans, 2016; Biegert, 2015
	Residue management	Burning crop residues (sugar cane (*Saccharum officinarum*) and pineapple (*Ananas comosus*)	Miller et al., 1997
Aquaponics		Vegetable production	Wongkiew et al., 2018
		Fish production	Hue et al., 2013
Forests		Tropical rainforest	Hall and Asner, 2007
		Montane forest	Hedin et al., 2003
		Fertility practices	Hall and Matson, 1999
		Invasive species	Litton et al., 2006; Litton et al., 2008; Litton et al., 2011; Hall and Asner, 2007

		Litter mineralization, and abiotic factors	Riley and Vitousek, 2000; Holtgrieve et al., 2006
		Forest fires	Howbaker et al., 2017
Peatlands/ wetlands			Chimner, 2004; Beilman et al. unpublished

Croplands. Pawlowski et al. (2017) reported GHG emissions from C4 tropical perennial grasses (i.e., sugarcane and napiergrass) were dominated by CO_2, as CH_4 oxidize and N_2O emissions are low, even following fertilizer application when N_2O efflux often occurs. Additionally, Matson et al. (1996) indicated N_2O and NO represents 0.03 to 0.5% of the applied N under Mollisols and Inceptisols, and 1.1–2.5% of the applied N under Andisols. On Maui, Pawlowski et al. (2017) reported deficit irrigation reduced GHG emissions from napiergrass but not for sugarcane. These results suggested napiergrass provides better net climate change mitigation and reduced water usage. Another study in napiergrass and Guinea grass reported soil CO_2 ranging from 325 to 1788 g C m^{-2} yr^{-1}, with no significant differences between accessions (Sumiyoshi et al., 2016). In 1992, Zacharriasen et al. (1993) reported that 50% of the N_2O emissions occurred during fertilization events, CH_4 uptake, and CO_2 emissions were generally higher in wet soils. Data gathered from Maui presents N_2O emissions ranging from 20 to 40 mg N m^{-2} yr^{-1} while data from the Leeward area (dry side) ranged from 11 to 30 mg N m^{-2} yr^{-1} from the Windward area (west side). Overall, studies indicate that denitrification is a critical source of N_2O in Maui, but that nitrification is more critical in Hawai'i Island, as a result of soil characteristics. Studies suggest that different patterns in N fluxes result from C, N, P availability, and oxygen status. The use of biochar for napiergrass increased yields by 14% and reduced GHG in a Mollisol (Meulemans, 2016). However, the use of biochar increases GHG emissions in an oxisol. There were no differences between both sites for methane emissions, but CH_4 uptake was higher in napier grass than in sweet corn. In the same study Meulemans (2016) reported N_2O emissions from corn were 6 to 17 times higher than in napier grass. Biergert (2016) reported after biochar application in napier grass, CO_2 and N_2O emissions are 9.0 kg CO_2-C $ha^{-1}$and 0.24 g N_2O-N ha^{-1}. The same study reported N_2O fluxes after biochar application with high moisture contents, especially in Oxisols. In Mollisols biochar reduced GHG emissions, which suggests biochar use needs to be classified and recommended for specific soils (Biegert, 2015).

Aquaponics. Wongkiew et al., (2018) data suggest aquaponics has a high potential for N recovery from aquaculture effluent via nitrate reduction and N assimilation into vegetables. High dissolved organic levels decreased N loss and nitrate concentrations in aquaponics. Additionally, aeration biofilters were found to reduce N loss, and fast-growing plants improved N use efficiency in aquaponics. The available GHG flux from aquaculture systems found here is from pak choi, lettuce, tomato, chive, and Chinese catfish. In aquaculture systems, under the use of 200 L tanks for raising Chinese catfish in a stocking density of 16 fishes (~235.5 g $fish^{-1}$), when the feeding rate increased from 10.0 to 30.0 mg N d^{-1}, the daily N_2O-N emissions increased from 14.8 ± 1.8 to 56.6 ± 4.6 mg N d^{-1} (Wongkiew et al., 2018). Furthermore, Wongkiew et al. (2018), studied N_2O emissions from pak choi, lettuce, tomato, chive growing in aquaponics, reported N_2O emissions varied from 18.2 to 24.1 mg N d^{-1}. Additional specific findings show that aeration biofilters (anoxic environment) did not reduce N_2O emissions and that N loss from the aquaponic system accounts for 0.72 to 1.03% of the N input.

Forests. Tropical forest emissions vary from 0.4 Tg N yr^{-1} for N_2O and 0.2 Tg N yr^{-1} for NO. Preliminary information from Hall and Matson (1999) reports tropical ecosystems with limited P soils are highly sensitive to N additions, which result in higher N losses than the one predicted by modeling systems on temperate forests. Hall and Matson (1999) measured soil emissions of N_2O) and NO after experimental additions of N in two tropical forests in Hawai‘i. A 300 yr old forest with a soil order Inceptisol, on Hawai'i, and a 4,100-kyr old forest in a soil order Oxisol on Kaua'i. Both locations are dominated by the native canopy tree, *Metrosideros polymorpha,* and are on non-eroded land surfaces with less than 6^{o} slope. Forests at these sites have never been cleared. At both locations, the geologic substrate is volcanic ash of similar chemical composition just differing by the soil order. Holgrieve et al. (2006) conclude N_2O fluxes in our mesic tropical forest appear to be mostly a result of the nitrification process, with denitrification becoming a more critical source in wetter sites. It is estimated that in a montane rain forest, the total flux is 0.40 Mg C ha^{-1} yr^{-1} (Giardina et al., 2014). Giardina et al. (2014) estimated that soil organic C turnover represents an estimated 0.39 Mg C ha^{-1} yr^{-1} (5%) of total soil efflux.

Long-term fertilization studies demonstrate that the primary production of *M. polymorpha* is limited by N in the 300-yr site and by P in the 4,100-kyr site. Results suggest there is a critical difference in response to N additions between N-limited and P-limited systems. The invasion of fire trees (*Morella faya*) in ‘ōhi‘a Hawaiian tropical forest has caused N-oxide emissions to increase 16-fold since its first occurrence during the past 40 years (Hall and Asner, 2007). Litton et. al (2008) reported that non native invasive grasses in the understory forest increase C emissions but don’t affect the total soil C pool.

More recent research by Holtgrieve (2006) studied the hurricane effects on N trace gas emissions on a rainforest. The N_2O fluxes in a Maui tropical forest appear primarily as a result of the nitrification process, with denitrification becoming a more critical source in wetter sites. Riley and Vitousek (2000) studied the effect of 1992 Hurricane Iniki’s disturbance on the native montane rain forest in the ecosystem to NO and N_2O emissions. Results from Herbert and Fownes (1999) showed a significant release of N, phosphorus, and potassium from litterfall during the first month after Hurricane Iniki. However, Riley and Vitousek (2000) mineralization rates were not constant during incubations and N emissions were correlated with water filled pore space and net nitrification. Net nitrification values were elevated after Iniki, with a mean net nitrification value three months following Iniki of 61 (+11) mg m^{-2} d^{-1} compared to mean values for the six pre-Iniki sampling dates, which ranged from 3 to 40 mg m^{-2} d^{-1}. In forests, studies suggest gaseous N losses are a result of ecosystem N availability, with low emissions in soils from young forests, compared with forests older than 20,000 yr (Hedin et al., 2003).

Peatlands/wetlands. Chimner et al. (2004) reported deep standing water in the peatlands Alakai Swamp in Kaua‘i and Flat Top Bog in Maui peatlands have low respiration rates, however, the lack of seasonal changes in the tropics, compared with other climatic zones, make tropical peatlands a higher annual CO_2 contributor. Beilman et al. (2019) reported the Pēpē‘ōae montane peatland in Molokai stores 144kg C m^{-2}.

Additional assessments. Other GHG emission assessments of note include Miller et al. (1997), Konan and Chan (2010), and State of Hawai‘i Department of Health (2019), all of which rely on available inventories. Miller et al. (1997) prepared a GHG inventory that included data from fertilizer use from 1986 to 1992, managed forest in Hawai‘i, abandoned land, and the burning of agricultural crop waste. Estimated N_2O emissions from fertilizer applications were 200.7 and 198.7 tons yr^{-1} during 1990 and 1994, respectively. Miller et al. (1997) report that the annual increment on C uptake from a managed forest in Hawai‘i is estimated to 113,225 t C yr^{-1}. The annual C uptake was considered sufficient to offset the total tonnage of all GHG emitted by the rest of the state's land uses. During 1997, there was an emerging trend of abandonment of land considering 59,500 acres. Miller et al. (1997) studied the abandoned land by its C uptake capacity similar to managed forests with an estimated 0.58 tons C $acre^{-1}$ yr^{-1}. Finally, data gathered from Miller et al. (1997) include the burning of crop wastes, especially pineapple and sugarcane fields prior to planting. Considering data collected from the sugarcane field burning during 1990 and 1994, the estimated GHG emissions were 11,548 and 9,303 tons respectively.

Konan and Chan (2010) studied the direct and indirect GHG emissions from Hawai‘i’s economic sectors impacted by tourism; Table 2 includes the GHG emissions reported from the crops and animals sector in Hawai‘i. Results indicated the crops and animal sectors are some of the least impacted sectors by tourism in Hawai‘i. By filling the inventory gaps, studies similar to Konan and Chan (2010) could turn into a life cycle analysis to determine the C footprint of working lands. This information is essential to provide evidence that will identify appropriate management practices and inform the development of policies that target soil C sequestration and ecosystem services of Hawai‘i natural and working lands.

Table 2 . Direct and indirect greenhouse gas emissions by final demand from Hawai‘i’s economic sectors impacted by tourism (Retrieved from: Konan and Chan, 2010)

Industry sector	CO_2 (metric tons)		CH_4 (metric tons CO_2-eq)		N_2O (metric tons CO_2-eq)	
	Resident	Visitor	Resident	Visitor	Resident	Visitor
Crops	11,928	3,348	19	5	86	24
Animal	8,380	259	13	0	59	2

Summary of knowledge.

Pastures. The role of grazed pastures and livestock systems in climate change mitigation has been overlooked in Hawai‘i. Current Hawai‘i GHG emission inventories report non-Hawai‘i data from reports of the Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change. Primary sources of emission are from enteric fermentation, which refers to methane production due to microbial fermentation in animals’ digestive processes, including dairy and beef cattle, sheep, goats, swine, and horses. Another source for the livestock sector is the treatment, storage, and transportation of livestock manure, a source of CH_4 anaerobic decomposition of manure and N_2O emissions to the nitrification and denitrification of organic N in the manure. None of these, nor soil GHG flux, have been directly quantified in Hawai‘i, to our knowledge.

Fertilizers. The GHG emissions from fertilizer applications result from the application of organic and inorganic sources of fertilizer and lime amendments. The use of fertilizer amendments has been a critical factor for soil health balance in agricultural production due to its capacity to balance the gap between nutrients required for the optimal crop development and the nutrient supplied by the soil (Brentrup, 2009). However, the manufacture and application of fertilizer and lime to agricultural soils is known to produce CO_2 emissions, enhance soil nitrification and denitrification rates, and could also result in leaching and volatilization, which produce N_2O emissions. In Hawai‘i, quantified GHG emissions are mainly from plantations, agricultural biofuels crops, and forests (Table 1). For example, Zacharriasen et al. (1993) reported that 50% of the total N_2O emissions occurred during fertilization events under an intensively managed sugarcane system. The same study reported that CH_4 and CO_2 emissions from this system were mainly a result of excess water in the soil. Also, from a sugarcane system, Matson et al. (1996) indicated that there are critical changes in NO and N_2O emissions after N application mainly due to soil C availability, fertilizer placement, and soil orders of Mollisols, Inceptisols, and Andisols. Moreover, Pawlowski et al. (2017) reported that in perennial crops, in Hawai‘i, CO_2 is the main GHG flux, since N_2O emissions were low and CH_4 oxidized.

Water fluctuations. Soil water content due to precipitation or irrigation events is known as factors causing fluctuations in soil GHG fluxes. Most of the N_2O emissions peaks from fertilization or climatic events occur within the first two weeks of the fertilizer application in crop systems and within 2-3 months under forest systems. Additional considerations, such as climatic events affecting GHG emissions, were studied by Riley and Vitousek (2000), who conclude that N trace emissions in a forest system are relatively insensitive to the disturbance of a hurricane event. This considering that most of the emissions occurred three months post-hurricane as a result of litter decomposition, which could have been predicted considering soil mineralization rates potential and water-filled pore space.

Natural cycles. Hall and Matson (1999) reported a critical effect on soil N_2O emission mechanisms due to N or phosphorus limited forest systems.

Soil GHG database gaps. Our study identifies gaps in the soil GHG inventory, including soil mineralization rates of the wide range of Hawai‘i soils, under the primary land management practices. More specifically, GHG fluxes from pasturelands and recently converted lands to pastures, orchards, and vegetable production systems. Another critical gap in understanding the efficiency of nutrient sources, including fertilizer, compost, manure, and biochar, in the primary soil management practices. For example, quantifying soil N and P relations in tropical forests, and soil fluxes resulted from nitrification and denitrification under andisols, mollisols, oxisols, and inceptisols.

2. Soil C resources

Overview. Soil C sequestration is mediated by inputs from plants and soil microbes and related to processes that protect soil organic matter from decomposition and loss. When CO_2 is removed from the atmosphere, transferred belowground, and stored in the soil C pool as soil organic C, sequestration may be considered to have occurred. The climate benefits of this sequestration are directly linked to inputs and transit time, or amount of time that C spends in the system (Sierra et al., 2021). An extensive body of research has shown the potential of the AFOLU sector to mitigate climate change by sequestering C and reducing atmospheric concentrations of GHG emissions (Lal, 2018). Climate smart practices increase soil health, soil C sequestration potential, and associated ecosystem services (Paustien et al., 2016). But, others have expressed caution about soil carbon sequestration as a climate mitigation tool (Amundson and Biardeau, 2018). Hawaiʻi's soils and ecosystems are so different from others (e.g., in soil organic C concentration and depth), that local or regional knowledge must be accessed to improve inventories and modeling tools that are used for decision support and policy. To begin opportunity assessment for the potential climate change benefits of soil C sequestration, an accurate soil C resource map is required. The following data compilation is of the known available site-specific measurements made in Hawaiʻi, which can supplement widely available national datasets to improve accounting for Hawaiʻi's soil C resource.

Data compilation.

Table 3. Index of references for soil C data in Hawaiʻi natural and working lands.

Working land sector	**Management systems**	**Land cover**	**References**
Agricultural land	Crop production		Cusack et al., 2013
		Sugarcane (*Saccharum officinarum)*	Burke et al., 2003; Pawlowski et al., 2018; Tirado-Corbalá et al., 2015
		Napiergrass (*Pennisetum purpureum)*	Pawlowski et al., 2017 and 2018; Sumiyoshi et al., 2017
		Guinea grass (*Megathyrsus maximus*)	Sumiyoshi et al., 2017
		Energycane (*Saccharum. officinarum x S. robustum cv. MOL-6081*)	Crow et al., 2020
	Orchards	Coffee	Youkhana and Idol, 2009; Youkhana and Idol, 2016
Ash soils- no			Perez, 2001

vegetation			
Pasture		Mixed	Burke et al., 2003; Cusack et al., 2013; Chadwick et al., 2007
		Kikuyu pasture (*Pennisetum clandestinum*)	Cusack et al., 2012; Nusslein and Tiedje, 1999; Torn et al., 1997; Townsend et al., 1995; Townsend et al., 1997; Blackmore and Vitousek, 2000; Crow et al. 2016
		Bufflegrass (*Cenchrus ciliaris*)	Torn et al., 1997
Grasslands			Kramer and Chadwick, 2016; Scowcroft et al., 2004; Chadwick et al., 2007
Shrublands			Kramer and Chadwick, 2016; Chadwick et al., 2007
Forests		Silvopasture	Blackmore and Vitousek, 2000; Krueger and Ryals (unpublished)
		Forest (non-specified, or diverse species)	Ares and Fownes, 2001; Burke et al., 2003; Scowcroft et al., 2004; McGrath, 2019; Melone et al., 2021
		Humid tropical forest	Giardina et al., 2003
		Tropical Dry forest	Elmore and Asner, 2006; Litton et al., 2006; Litton et al., 2008; Litton et al., 2011; Chadwick et al., 2007
		Tropical rainforest	Hall and Matson 2003; Hall and Asner, 2007; Rillig et al., 2001
		Montane forest	Bothwell et al., 2014; Gower and Vitousek, 1989; Herbert and Fownes, 1999; Hobbie, 2000; Idol et al., 2007; Kitayama et al., 1997; Riley and Vitousek, 1995; Rillig et al., 2001; Schuur et al, 2001; Selmants et al., 2014; Selmants et al., 2016; Chadwick et al., 2007; Hedin et al., 2003; Giardina et al., 2014
		Native forest/ Forest reserves	Austin, 2002; Austin and Vitousek, 1998; Chadwick et al., 2007; Chorover et al., 2004; Crews et al., 1995; Cusack et al., 2012; Hughes and Denslow, 2005; Hughes and Uowolo, 2006; Kao-Kniffin and Balser, 2008; Kramer et al., 2012; Mascaro et al., 2012; Neff et al., 2000; Osher et al., 2003; Sanderman and Kramer, 2013; Stewart et al., 2011; Giardina et al. 2014
		Eucalyptus and Albizia	Binkley et al., 1992; Kaye et al., 2000; Resh et al., 2002
		Eucalyptus plantation	Giardina and Ryan, 2002; Binkley et al., 1992; Kaye et al., 2000; Resh et al., 2002; Ryan et al., 2008; Crow et al., 2016; Zou and Bashkin, 1998
		Koa forest	Idol et al., 2007; Litton et al., 2011; Scowcroft et

		(*Acacia koa*)	al., 2004; Ares and Fownes, 2001;
		‘Ō‘hia forest (*Metrosideros polymorpha*)	Grant et al., 2019; Hobbie and Vitousek, 2000; Hughes and Uowolo, 2006; Kao-Kniffin and Balser, 2008; Kramer et al., 2012; Mascaro et al., 2012; Neff et al., 2000; Nusslein and Tiedje, 1999; Rilling et al., 2001; Sandermand and Kramer, 2013; Torn et al., 1997; Torn et al., 2005; Townsend et al., 1995; Townsend et al., 1997; Giardina et al., 2014
		Fern (*Dicranopteris linearis*)	Stewart et al., 2011
		Ōlapa (*Cheirodendron trigynum*)	Stewart et al., 2011
	Forest with Invasive species		Litton et al., 2006; Litton et al., 2008; Litton et al., 2011; Melone et al. 2021
	Soil fertility/ Nutrient management practices		Giardina et al., 2003; Giardina et al., 2004; Gower and Vitousek, 1989; Hobbie , 2000; Hobbie and Vitousek, 2000; Neff et al., 2000; Ryan et al., 2008; Idol et al., 2007
Converted lands	Abandoned to forest	Pasture-abandoned/grassland-koa forest	Scowcroft et al., 2004; Idol et al., 2007
	Plantation to Pasture, Secondary forest or forest		Bashkin and Binkley, 1998; Binkley and Resh, 1999; Binkley et al., 2004; Guo and Gifford, 2002; Kaye et al., 2000; Zou and Bashkin, 1998
	Forest to Pasture, crop or managed forest		Guo and Gifford, 2002; Nüsslein and Tiedje, 1999
	Pasture to Forest, secondary Forest, plantation or crop		Crow et al., 2016; Guo and Gifford, 2002
	Intensive cultivation to perennial grass with zero tillage		Crow et al., 2020
Shrubland			Chadwick et al., 2007
Peatlands/ Wetlands			Beilman et al., 2019

Croplands. Cusack et al. (2012) studied the long-term impact of agricultural practices on soil C pools in Hawai‘i soils and found that many farming practices were associated with persistent, negative changes in soil C chemistry. Hawai‘i sugarcane plantations that maintained conventional harvest practices were a significant C source (Pawlowski et al., 2018). Efforts on crops for energy or fuel production on former sugarcane plantations should concentrate on ratoon-harvested crops, such as napiergrass, which maintain yields under zero tillage and deficit irrigation while sequestering C and mitigating GHG emissions (Sumiyoshi et al., 2017; Pawlowski et al., 2018). Specialized cultivars are an option to increase C sequestration in crop lands. Crow et al. (2020) estimated soil C stocks of 159.5 Mg C ha^{-1} in energy cane, 181.4 Mg C ha^{-1} in napier grass, and 174.9 in sugar cane. In another study, Crow et al. (2020) and Pawlowski et al. (2018) reported soil C stock in the first meter of soil in Andisols, Oxisols, Mollisols and Aridisols (Fig. 1). Tirado-Corbalá et al. (2015) demonstrated how cultivars that can navigate deeper layers under different soil types have higher soil C accumulation. Similarly, Sumiyoshi et al. (2017) conducted a structural equation modeling of napiergrass varieties that revealed root lignin concentrations are the most important driver of soil organic C pools, specifically that low-lignin roots lead to greater soil C. In orchards, a cut and carry mulching system and practices that increase litter, such as tree pruning, can increase total soil C by 2.90 C Mg ha^{-1}, and increased yields similar to a full-sun production system (Youkhana and Idol, 2009; Youkhana and Idol, 2016).

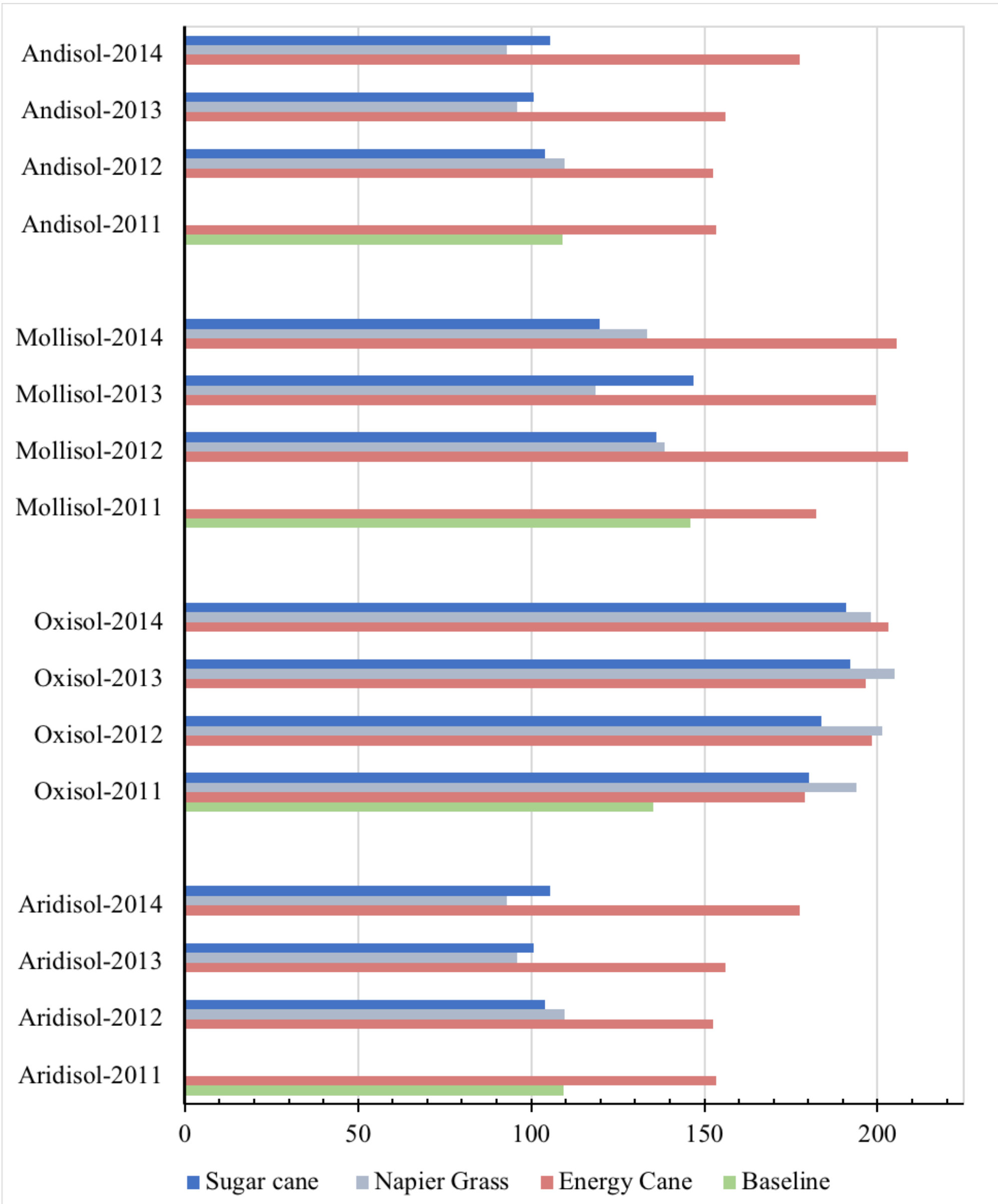

Figure 1. *Measured soil C stocks (Mg C ha^{-1}) in the first 1 m deep in bioenergy crops and bare soil (baseline) over the course of a 4-year trial in four different soil orders in Maui, HI (Pawlowski et al., 2018; Crow et al., 2020).*

No vegetation. Under volcanic ash soils, Pérez (2001) reported dead tissue from silversword rosettes (Argyroxiphium sandwicense) increases soil organic C, compared with base area and areas with live silversword rosettes.

Peatlands/wetlands. Beilman et al. (2019) reported the Pēpēʻōpae montane peatland stores 144 kg C m^{-2}.

Pasture. Burke et al. (2003) reported on the importance of organic residues and minimized soil physical disturbance in pasture management in order to maintain soil C. The same study compared soil C between forest, pasture lands, and sugarcane plantations, indicating soils under sugarcane plantation have significantly less C than forests and pastures. Elmore and Asner (2006) reported that pasture soil C stocks (4.5 to 9.5 kg C m^{-2}) were generally less or equal to soil C stocks in forests (9.7 to 12.7 kg C m^{-2}) in a dry tropical forest in Pu‘u Wa‘awa‘a. On average, there was 52.4 kg C m^{-2} in the top 1 m of high quality pasture in Andisols along the Hamakua Coast of Hawai‘i Island (Crow et al., 2016). In Maui, Krueger (unpublished) is studying the total soil C within four different forages at different soil depths (Table 4).

Table 4. Average soil C stocks by the forages kikuyu (*Pennisetum clandestinum*), Plantago (*Plantago lanceolata*), velvet (*Mucuna pruriens*) and vernal (*Medicago sativa*) and depth in Maui (Unpublished data, Nick Krueger).

Soil depth	**Kikuyu**	**Plantago**	**Velvet**	**Vernal**
cm	**Mg C ha^{-1}**	**Mg C ha^{-1}**	**Mg C ha^{-1}**	**Mg C ha^{-1}**
0-15	113.1	79.7	95.4	105.4
15-30	87.6	98.0	75.3	86.9
30-50	106.1	111.8	105.3	102.6
50-75	120.6	125.7	113.8	123.2
75-100	115.4	148.1	137.2	121.6

Grasslands. Carbon stock across sites from 3,560 to 3,030 m in Mauna Kea sequence increased from 3.1 up to 118.9 Mg C ha^{-1} (Kramer and Chadwick, 2016). In Mauna Kea, Scowcroft et al. (2004) reported total soil C values of 158 and 179 g C kg^{-1} in a slope and the bottom of the mountain, respectively.

Forests. In Honaunau forest in Hawai‘i Island, Ares and Fownes (2001) reported that *F. uhdei* in elevations from 730 to 1,400 m ranges from 1.08 to 2.05 % of soil organic C. While a mix stand of *A. koa* and *F. uhdei* in 1,360 to 1,420 m elevation ranges from 21.9 to 35% of soil organic C. In Hakalau forest in Big Island, Scowcroft et al. (2004) reported total C values for forest, planted koa and a grassland of 212, 182, and 158 g C kg^{-1}, respectively, in a slope, and 280, 227, and 179 g C kg^{-1} in the bottom. In an agroforest restoration, Melone et al. (2020) reported a mean cumulative soil C stock of 136.4 Mg. In Pu‘u Wa‘awa‘a Ranch on the north side of Hualalai volcano, on the Island of Hawai’i, Elmore and Asner (2006) reported C stocks from pasture vegetation from 4.5 to 9.5 kg C m^{-2} varying by grazing intensity. Forest soils in the same location ranged from 9.7 to 12.7 kg C m^{-2}. In a predominantly ‘ōhi‘a managed forest with N limited management near Kīlauea in the Island of Hawai‘i, N limitation results in a total soil C of 8.0 kg C m^{-2}, compared with 7.2 kg C m^{-2} with no management (control) (Hall and Matson, 2003). Same study reported a P limited forest in Kaua‘i resulted in a total soil C of 9.94 kg C m^{-2}, compared with 9.3 kg C m^{-2} with no management (control). Schuur et al. (2001) studied six montane wet forests across precipitation gradients near Haleakala volcano demonstrating soil C storage ranged from 30.9 to 62.5 kg C m^{-2} and increased by a factor of 1.7 kg C m^{-2} with the increase in precipitation gradient. In a tropical montane wet forest, Giardina et al. (2014) reported that the long term and whole ecosystem warming accelerates below C processes but does not impact soil organic C storage. (See Box 1 for details).

Box 1. Protection and valuation of key high-C forests and soils.

Andisols, soils that developed from volcanic ash deposits, are the most extensive soil order in the state of Hawai'i, covering over 800,000 acres and comprising 39% of total land area (Deenik et al. 2007). The volcanic ash transforms into clay minerals that are poorly or non-crystalline in form. This disorganized form gives them immense surface area on which to bind with C found in organic matter that enters the soil as dissolved organic matter, litter decomposition products, or the microbiome. Many Andisols occur in areas with very high rainfall, and in Hawai'i's tropical climate this means very high productivity – i.e., large trees, immense understory and ground cover, and all the associated roots and rhizosphere microbiome – that supplies high inputs to the system (Fig. 2). These inputs may bind to clay surfaces and be stabilized to persist in the soil profile for very, very long periods of time. These systems have both high C inputs to the system and long timeframes for C flow from photosynthesis back to respiration, two factors that are critical to obtaining a climate benefit from sequestration. Emissions of C remain in the atmosphere and cause climate change on a much longer timeframe than most soils can sequester. However, supercharged volcanic ash soils, such as those in Hawai'i are some of the only systems where the climate benefit of sequestration in old growth trees and the Andisols they grow on may be on the same scale (see Box 4 for more details). Therefore, continued protection of these super C rich systems from deforestation and degradation is tantamount.

Figure 2 *Photo from a site along the Hamakua Coast of the Island of Hawai'i showing an Andisol soil profile with measuring stick marking 10 cm increments and soil showing 10-cm incremental sampling holes down the profile (photo credit, Susan Crow).*

Accurate assessment of standing stocks and annual fluxes in resource maps and inventories is crucial to demonstrate their true value in the currency of climate change, C. In a tropical montane (wet) forest, Giardina et al. (2014) reported that the long term and whole ecosystem warming accelerates some C processes at the forest floor-soil interface, but does not impact total soil organic C storage. Giardina et al. 2014 reported 34.6 Mg C ha^{-1} in soil C stores in just the 0 to 10 cm section of mineral soil and over 240 Mg C ha^{-1} in the 0 to 91.5 cm section of soil. In comparison, widely applied 2019 Refinement of 2006 IPCC Guidelines default reference condition soil organic C stocks for mineral soils (in Mg C ha^{-1} in 0 to 30 cm depth) for Volcanic soils (i.e., Andisols) are 50

± 90%, 70 ± 90%, 77 ± 27% and 96 ± 31% for tropical dry, moist, wet, and montane climate zones respectively (Table 2.3 updated in IPCC Guidelines, AFOLU Generic Methods chapter and section). Mismatches between internationally accepted equations for determining soil C stocks, at predetermined shallow depth intervals, and potential changes over time means that these, and other similar, systems may be undervalued as a potential land-based climate mitigation strategy.

Converted lands. On Maui, following 120 years of intensive sugarcane cultivation, soil C stocks was 18.0 kg C ha^{-1} in the top 1 m. However, just four years of perennial grass (energy cane) cultivation with zero tillage management increased soil C stock significantly to 22.6 kg C ha^{-1} in the top 1 m (Crow et al., 2020). (see Box 2 for more details) When comparing former sugarcane lands converted to forest and pasture for 20 yr in similar soil types, Li and Matthews (2010) found that the forest site had a significantly higher C stock (1.5 kg m^{-2} more). In contrast, Baskin and Binkley (1998) and Giardina et al. (2004) found no increase in total soil organic C when lands were converted from sugarcane plantations to forests. Burke et al. (2003) reported that a 90 yr old pasture has less soil C depletion in the 0-20 cm of soil than a 90 year old sugarcane plantation. Scowcroft et al. (2004) reported the re-establishment of *Acacia koa* in previous pasture land resulted in soil physical and chemical changes, but did not alter total soil C within the first 10 years of planting. Similarly, there was no difference in soil C stocks measured to about 1 m between paired plots of high quality pasture and 6-10 years of eucalyptus plantation on previous pasture lands along the Hamakua Coast of Hawai'i Island (Crow et al. 2016). However, tree plantation resulted in losses of soil C in some high elevation areas (see Box 3 for more details). Litton et al. (2006) reported that the conversion of Hawaiian dry forest to grasslands due to non-native grass invasion reduces soil C storage at landscape and regional scales. Melone et al. (2021) reported a mean soil C stock of 13.6 kg C m^{-2} in approximately 0-80 cm of invaded forest in transition to agroforestry as part of a biocultural restoration on O'ahu.

Box 2. **Improved management to regenerate abandoned agricultural lands.**

Perennial grasses are managed in a zero-tillage system that keeps the belowground environment intact even during harvest of the aboveground biomass and provide an example of an agroecosystem that can help achieve multiple goals, such as renewable fuel production and soil C sequestration (Pawlowski et al., 2017). High yielding grasses have extensive roots. Roots with low lignin concentration decompose quickly, some of that root material is released as CO_2, but some is retained in soil and builds up organic matter. (Sumiyoshi et al., 2016). As the aboveground biomass is harvested, the root system remains intact (Fig. 3). Some roots die and decay. During this process the soil microbial population grows in response to the root input and root tissues are transformed. The root-derived organic matter is transferred from particulates (roots and microbes) to aggregates (associated with the roots and soil organisms) to mineral surfaces (organic compounds binding to mineral surfaces at molecular level). (Crow et al., 2018) This pathway, and the rate of transfers between forms, or pools, of C is critical to climate change mitigation because as C accumulates and stabilizes, meaning it is protected from further decomposition and release back to the atmosphere, sequestration is driven by association with the mineral fraction. In the tropics, the rate of transfer is rapid and the pathways are more dynamic than in temperate systems.

Even under warmer conditions, even faster transfers means that C will continue to accumulate and sequester C (Crow and Sierra, 2018).

On Maui, former sugarcane land accumulated 11.4 Mg C ha^{-1} yr^{-1} for 5 years following plantation of energycane, a tropical perennial C4 grass managed as a zero-tillage ratoon harvest system. Further, C inputs to the belowground system persisted for over a century (i.e., the mean transit time of the average C molecule was 170 yr and median was 110 yr) (Crow et al., 2020). A century of intensive cultivation of monocrop sugarcane and pineapple left a legacy of degraded soils across the Hawaiian landscape. The degradation of tropical soils is similarly widespread globally, and depleted lands everywhere are increasingly targeted for land-based climate action and other efforts to restore ecosystem function. In Hawaiʻi, post-plantation era soils responded rapidly and to a large degree to improved management strategies showing the very high potential for C sequestration and associated improvements in soil health and continued productivity.

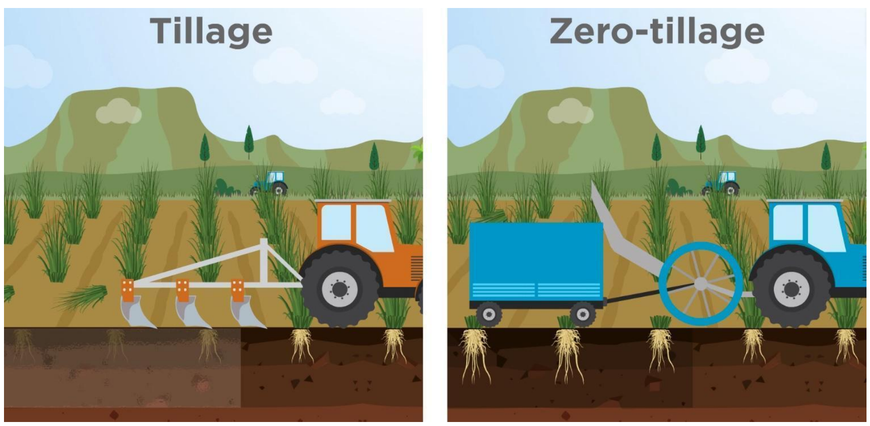

Figure 3. *Depiction of the belowground system and roots left intact with a zero-tillage management system of tropical perennial grasses compared to a tillage system that removes all biomass and roots and overturns the soil. (From Soil Carbon Drawdown: How? https://www.youtube.com/watch?v=xXo-9x1bSDU, Susan Crow)*

Box 3. Need for local measurements to verify assumptions before taking actions

The Hamakua Coast of the Island of Hawaiʻi is a mosaic of land uses, including protected forests, high productivity pastures, and forest plantations, all on Andisols in their peak potential to stabilize and store soil C. In some areas, approximately 100 years ago native old growth ʻōhiʻa and koa forest was replaced with pasture for grazing. Then, about 15 years ago some of that pasture was afforested in eucalyptus (Fig. 4). Not all soil C is in the same form or has the same persistence in the soil profile, and preliminary work showed that conversion to pasture shifted the majority of C from old, mineral-protected pools to more recent, particulate and aggregate-protected pools. The particulate pool and aggregate pools declined again for the soil to be dominated again with mineral-protected C pools when reforested in plantation, even after just 15 years (Crow et al., 2016). To test whether afforestation of high-quality pasture on Andisols along the Hamakua Coast resulted in soil C changes, paired locations of pasture and eucalyptus plantation were measured for above and belowground C stocks 7-10 years after plantation.

In the eucalyptus plantation, total soil C stock to 1 meter was nearly 10 times the tree biomass. (57.2 Mg C ha^{-1} in tree biomass versus 531 Mg C ha^{-1} in ~1 m of soil). On average across six pairs of pasture and eucalyptus stands, there was virtually no change in soil C stock with plantation. However, some of the plots lost more soil C as a result of plantation than the trees gained through photosynthesis in the same time period (Crow et al., 2016). In contrast, some other plots gained nearly as much in soil C as they also gained in tree C. Closer inspection of the location where losses occurred compared to gains revealed that higher elevation pastures lost the most. In those areas, grasses thrive and trees are less productive in cooler temperatures. Further investigation of the soil, and various C pools that comprise it, confirmed that losses of C-rich particulate and aggregate-protected C were immense following land preparation and tree plantation. In lower elevations, the grasses had not accumulated belowground C to the same degree as higher elevations and therefore losses were not as profound. Instead, gains in mineral-protected C were predominant.

Assumptions and misconceptions about the net ecosystem effect (i.e., adding up all the gains and losses and seeing the balance) of afforestation can contribute to unrealistic expectations about the climate benefits of some actions. Further, missing or undervaluation of soil C contributions to the net effect of a land use change skews any opportunity assessment and potentially leaves out critical stakeholders with great potential value to achieving decarbonization within the agricultural sector.

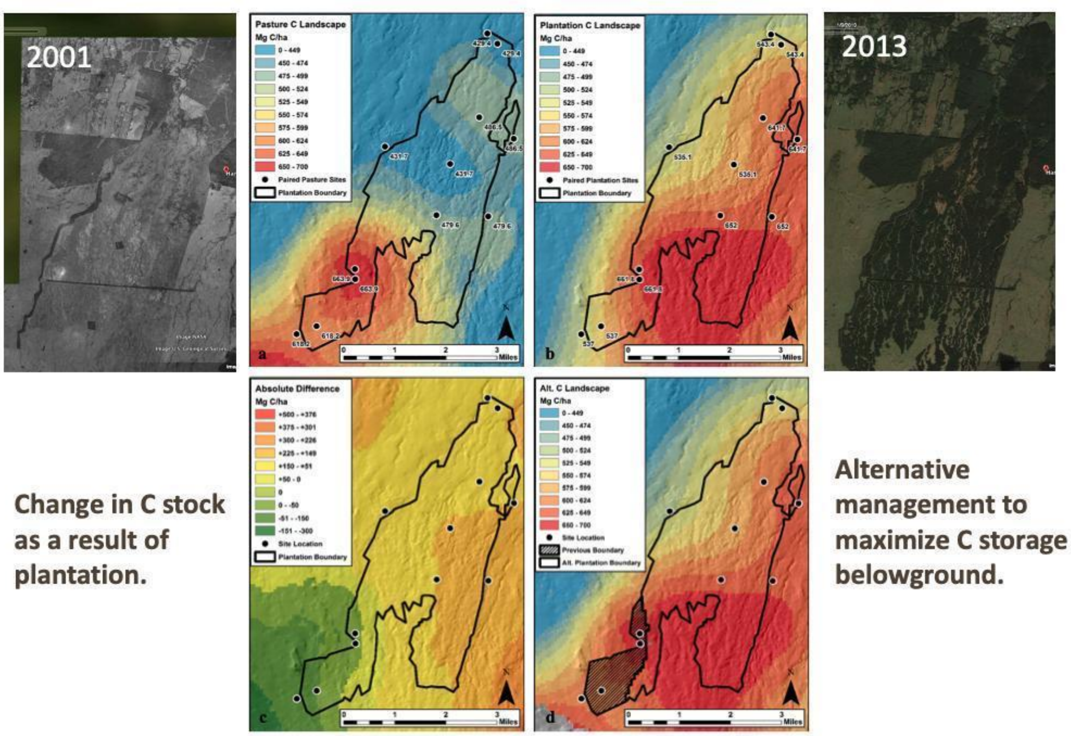

__Figure 4.__ Google Earth images from 2001(top outer left) and 2013 (top outer right) show the conversion of pasture to Eucalyptus plantation on a parcel of land along the Hamakua Coast of

the Island of Hawai'i. On the same timeframe of afforestation, 1 m soil C stocks changed (top inner left versus inner right) and the difference between the two (bottom left) shows losses (green) in some areas and gains (yellow/orange) in others. Alternative management choices, specifically that preserved the pasture in higher elevation areas that experienced soil C losses (bottom right), would have maximized the landscape-level C storage. Credit for this analysis: adapted from Crow et al. 2016 by Michelle Lazaro and Dr. Tomoaki Miura.

Additional Assessments. The State of Hawai‘i Department of Health (2019) reported the AFOLU sector contributes 1.10 MMT CO_2-eq. during 2015, which constitutes 5.2% of total Hawai‘i GHG emissions. The main sources of GHG from Hawai‘i's AFOLU sector are enteric fermentation (22%), forest fires (10%), agricultural soil management (13%), manure management (4%), field burning (0.5%), and urea application (0.1%). Selmants et al. (2017) USGS "Baselines and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawaii" estimated the total C stored in terrestrial ecosystems across the Hawaiian Islands was 258 TgC (Table 5). Hawai‘i Island stored 58% (136 TgC) of the total C in the Hawaiian Islands, with forest, shrubland, and grasslands as the main land covers. Maui, O‘ahu, and Kaua‘i represented 8 to 12 % of the total land area of Hawai‘i islands, each with a 10-14 percent of the estimated total C sink. Table 5 and 6 summarize the estimated ecosystem C stored in the Hawai‘i islands by islands, and by the main ecosystems. Sleeter et al. (2017) projected a total C storage increase of 6% for a total of 267.6 TgC in 2061 for the state of Hawai‘i.

Table 5. Estimate of ecosystem C stored in Hawai‘i islands (Fragment of Table 6.4 in Selmants et. al., 2017).

Island	**Area (km^2)**	**Soil organic C (TgC)**
Hawai‘i	10,453	146.1
Kaho‘olawe	115	0.8
Kaua‘i	1,428	33.5
Lāna‘i	365	2.7
Maui	1,898	32.5
Moloka‘i	672	10.8
O‘ahu	1,539	31.5
Total	**16,470**	**257.9**

Table 6. Estimates of ecosystem C stored in Hawai‘i by C pool for each ecosystem type (Fragment of Table 6.5 in Selmants et. al. (2017))

Ecosystem	**Area (km^2)**	**Soil organic C (TgC)**
Native dry forest	302	1.8
Invaded dry forest	635	3.6
Native mesic-wet forest	3,148	58.9

Invaded mesic-wet forest	1,529	27.6
Alien tree plantations	243	5.1
Shrublands	2,719	20.6
Grasslands	2,783	35.6
Bare (sparse vegetation)	3,111	5.7
Total	**14,470**	**158.9**

Soil C database gaps. This summary identifies gaps in soil C data from vegetable production systems, pastures (meat and dairy industry), agroecosystems, orchard (coffee, macadamia nuts, and other tropical fruits), and recently converted lands (plantation to forest, plantation to pastures, pastures to forest).

Using the database. It is possible to preserve, restore, and enhance soil C sequestration and ecosystem services from natural and working lands by (1) identifying the current status (managed, unmanaged, abandoned), and (2) understanding the ecosystem services, soil C stocks, and of the natural and working lands. For example, different soils have varying potential to sequester soil C (Lal, 2018). Therefore, a soil C resource map (i.e., a spatially explicit map that interpolates current soil C stocks) can help identify areas of focus for climate-action and improved C management. For example, the volcanic ash-derived soils (Andisols) common to Hawai‘i are known to have high C sequestration potential due to the presence of poorly and non crystalline minerals that sorb and protect C once it enters the soil. Another example are unmanaged lands with degraded soils, recently unmanaged post-plantation that is available for improved agricultural land use or afforestation. Using this information, it is possible to identify and focus on areas that have the greatest potential to mitigate climate change (Fisher et al. 2008). Lastly, a soil C baseline serves as a reference point to track climate change mitigation and ecosystem service goals and benchmarks. Currently, many decision-support tools rely on soil C maps based solely on National Cooperative Soil Survey (NCSS) data — while the data are detailed, there are limitations. For example, in some areas NCSS data were only approximately 70% accurate due to age of data and the dynamic nature of soil-landscape relationships (Brevik et al., 2003; Drohan et al., 2003).

SoilGrids is a system for global digital soil mapping that uses machine-learning to interpolate soil properties, namely soil C stocks. SoilGrids joins soil and environmental covariates data (land cover, terrain analysis, climate, etc.) to predict soil organic C stocks. We used the compiled soil C data for Hawai‘i from published literature, unpublished works, NCSS, and the NRCS Rapid Carbon Assessment (RaCA) to create an updated soil C map (the original used only NCSS data) using machine-learning to iteratively predict and validate the resulting soil C map using the SoilGrids version 2017 (1.0) methodology (Hengl *et al.,* 2017). Version 1.0 (2017) used the “interpolate first calculate later” method and version 2.0 uses an improved “calculate first interpolate later” method. SoilGrids version 2.0 data are publicly available; however, the methodology and coding has not yet been published and released so we were unable to create an updated map.

To create soil organic carbon (SOC) prediction maps, we: 1) calculated soil organic C stocks from measured soil data, 2) calculated C densities sums from 0 to 30 cm, 3) calibrated and ran a Quantile Random Forest model using 5% and 95% quantiles, and 4) cross-validated interpolations with a 10-fold comparison to the soil data. The model also requires covariate data; much of this data is calculated from digital elevation models (DEMs) and climate data, and includes land cover data. The mean prediction map represents the expected value, and is an unbiased prediction of SOC stocks (Fig. 5). The median (5% quantile) prediction map represents the value that there is a 50% probability that the true value is greater and 50% probability that it is smaller. For SOC stock predictions maps, the mean will be greater than the median because the data is skewed to the right. The resulting maps are at a coarse 250 m resolution, with goals of finer 100 m resolution. Additionally, the organic layers of soil are removed from the calculations and models. The maps are 30 to 70% accurate due to a variety of reasons: limited data, poor covariate data, and modelling choices. A layer of uncertainty – the ratio between the interquartile range (90% prediction interval width) and the median – can be calculated and displayed.

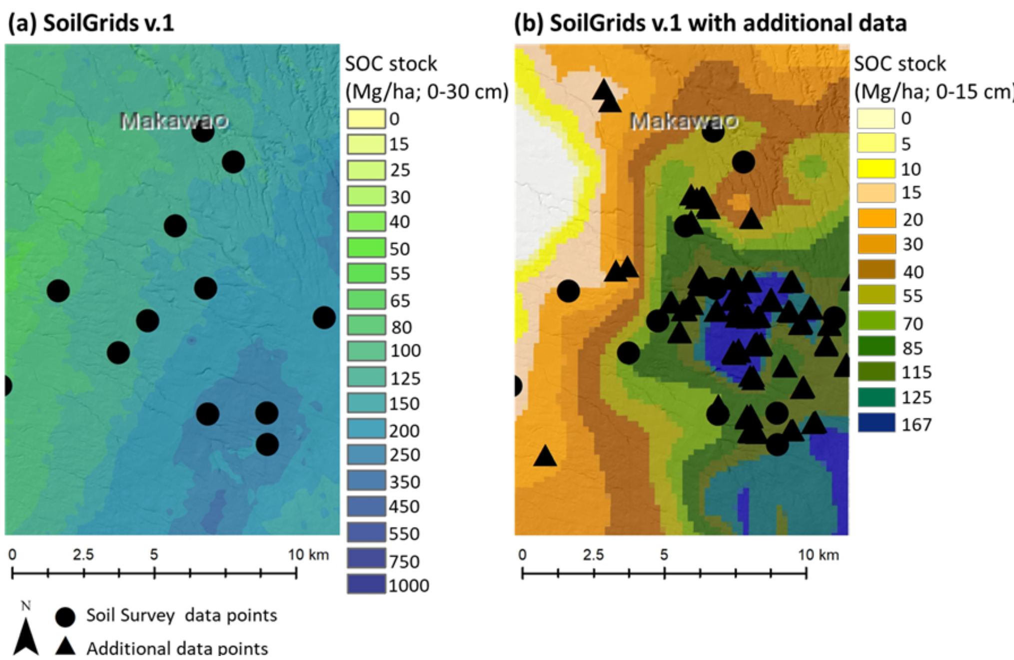

Figure 5. Soil organic carbon (SOC) map of Maui at the half-island scale. (a) SoilGrids version 1 – SOC map using only Soil Survey data to a 30 cm depth. (b) SoilGrids version 1 — SOC map using additional compiled measured data. This map only predicts a soil depth of 15 cm.

While our updates are an improvement, there are still known issues that decrease the accuracy of our soil C stock maps. SoilGrids, both Versions 1.0 and 2.0, are known to underestimate high organic soils. High organic content soils are extensive across the Hawaiian Islands. Additionally, Hawai‘i LiDAR (which stands for Light Detection and Ranging and is a remote sensing method) and digital elevation maps are not comprehensively wall-to-wall due to cloud coverage, especially in the context of microclimates and topography dynamics and out-of-date and costly to update. Lastly, our compiled data and future data we will continue to compile requires extensive metadata standardization. Some data assumptions have to be made to achieve data standardization. Our future goals are to more accurately predict soil organic C stock in finer resolution maps, and to account for deeper depths.

Box 4. Climate Benefits of Sequestration.

A soil C resource map is a best effort to know what the amount of soil C is in Hawai‘i's systems. It is presented as a stock, or a point-in time measurement, however the map consists of data collected at various points in time in Hawai‘i's recent history. Hawai‘i's landscapes are in transition: first from natural condition to ancestral Hawaiian practice, then to post-Western contact deforestation and intensive mon-cropping, now to post-plantation era urbanization, conservation, and diversification of broadly defined agriculture to meet multiple competing needs for water, food, energy, and fiber. Because of this transitional nature, mathematical models developed for Hawai‘i's soils and systems are essential to determining the potential climate benefits derived from nature-based actions in natural and working lands. New C inputs to ecosystems (including soils) are not expected to remain for very long and only small proportions of inputs get stabilized in forms of biomass or associated with soil minerals that count as true "sequestration."

Although soils are a promising place to store C and mediate emissions, long time scales are required to store C in amounts that are relevant to climate change. Therefore, it is critical to consider soil C more holistically. First, soil C is a primary component of soil organic matter and soil organic matter plays a central role in soil health. Soil health is connected to multiple ecosystem services (including climate change mitigation and adaptation through resiliency) that improve human well-being. Second, soil management for soil C is one part of a sustainable food system. Computations that include the warming benefit of C sequestration in ecosystems allow a direct comparison to the warming benefit of avoided emissions within the same system. For example, soil C accumulating in a pasture or farmer's field as a result of improved management practices is beneficial to climate. However, within the same system the avoided emissions due to imported food and fertilizer likely far outweigh the climate benefits of sequestration. Yet, when considered as a whole system that also acknowledges the broader benefits of improved landscape condition, human well-being, and climate resilience resulting from soil health, the potential for greater climate readiness is vastly expanded.

In a recent paper by Sierra et al. (2021) and Sierra and Crow (in preparation) we define C sequestration as *the storage of a certain amount of C input over a certain period of time within a system. It can be quantified as the area under the curve illustrating the fate of C input as it flows through an ecosystem over time*. Further, we define the climate benefit of C sequestration as *the radiative forcing effect avoided by an amount of C inputs to the soil stored over a specific time horizon*. The concept can be used to compare different soils or management in terms of the avoided warming they can provide as an ecosystem service. For its computation, it is necessary to have a model that predicts the fate of the inputs of C to the soil and the timing of C return to the atmosphere from respiration. Practically any SOC model can provide these predictions, and it is possible to compare predictions of the climate benefit of sequestration from different models. However, ecosystem process-based models that accurately forecast soil C, yields, and GHG flux are largely lacking for most of Hawaiʻi's ecosystems.

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3. Land use classification GIS layers for Hawaiʻi

Overview. Climate-smart management should occur and result in diverse types of multifunctioning landscapes (Duarte *et al.,* 2018). For a holistic approach to climate-action, we must consider both natural and working lands and strive to preserve natural resources and increase climate-smart agricultural production. A land-use map should combine natural and working lands based on available data and be updated via participatory feedback from stakeholders and any new data. Spatially explicit land management data helps us identify current the land uses and spatial characteristics of ecosystem services (i.e., current land uses and C sequestration) (Fisher *et al.,* 2009; Liao *et al.,* 2020). By having an updated spatially explicit land use/cover map we can prioritize areas by their management or by its current or potential soil C stocks and ecosystems services (Fisher et al., 2009; Metzger and Brancalion, 2016). All available land use GIS layers for Hawaiʻi (Table 6) were compiled and projected in NAD 83 Zone 4N using ArcGIS 10.4.1 (ESRI, 2020). All datasets in Table 7 can be downloaded from the HI_Landcover_all.zip folder included.

Layer compilation.

Table 7. Compiled list of available land use/cover datasets for Hawaiian Islands

Land cover data layer	Description	Citation
Important Agricultural Lands (IAL)	Classification based on importance of agricultural lands; integrates ALISH; criteria: https://www.capitol.hawaii.gov/hrscurrent/Vol04_Ch0201-0257/HRS0205/HRS_0205-0044.htm	State Land Use Commission 2019
Carbon Assessment of Hawaiʻi Land Cover (CAH)	Land cover by biomes & invasion status; integration of HI-GAP, C-CAP, LF, and updates using very high resolution imagery	U.S. Geological Survey 2017
Agricultural Land Use Baseline (ALUB)	The 2015 Hawaiʻi Statewide Agricultural Land Use Baseline layer was created to provide a snapshot of contemporary commercial agricultural land use activity in Hawaiʻi. The purpose of this layer was to help define the areas, circumstances, and resources that drive the agricultural production taking place throughout the state.	Perroy, R., and Collier, E. (2021). *2020 Update to the Hawaiʻi Statewide Agricultural Land Use Baseline*.

Pre-contact Native Hawaiian Footprint	Map of pre-contact Native Hawaiian land use based on archaeological evidence, information on native habitats, and natural condition information.	The Nature Conservatory & Office Hawaiian Affairs 2014
Coast Change Analysis Program Land Cover (C-CAP)	Land cover classification using multispectral analyses based on Landsat and high-resolution imagery; specifically for coastal lands	NOAA 1992-2012
Landfire Vegetation (LF)	Vegetation cover created by regression tree landscape models based on field data, satellite imagery, biophysical gradients	U.S. Geological Survey 2009
Gap Analysis Program Land Cover (HI-GAP)	Land cover using classification and regression trees based on Landsat TM satellite imagery 1999-2001, supplemented with Multi-Resolution Land Characteristic imagery and environmental data	Gon et al. 2006
Agricultural Land Use Maps (ALUM)	Hand drafted maps from State Planning and Development Section & US Soil Conservation Service information; digitized	State Department of Agriculture 1978-1980
Agricultural Lands Importance (ALISH)	Classified important agricultural lands into prime, unique, and other important lands; hand drafted; digitized	State Department of Agriculture 1977
Land Use Cover (LULC)	Manual interpretation based on 1970's aerial photography	U.S. Geological Survey 1976
Land Study Bureau (LSB)	Land classification and productivity rating based on aerial photography and topographic maps; hand drafted onto paper; digitized	Land Study Bureau 1972

For an initial assessment, we primarily used Carbon Assessment of Hawaiʻi (CAH) land cover and Agricultural Land Use Baseline (ALUB) datasets. The CAH integrated and updated several other GIS data layers listed in Table 7. The ALUB was not included in CAH and was made in collaboration with stakeholders and landowners — thus assumed to be the most accurate. As an example, we spatially joined CAH and ALUB using the Overlay Analysis Tool for Maui (Fig. 6). Additionally, we included land cover data from our Hawaiʻi Soil Health project sites because we have ground-truthed these data and personally work with the land owners and stakeholders (currently, approximately 70 sites). However, the Hawaiʻi Soil Health land cover data is currently only point data — further outreach with our stakeholders is needed to create spatially explicit polygons.

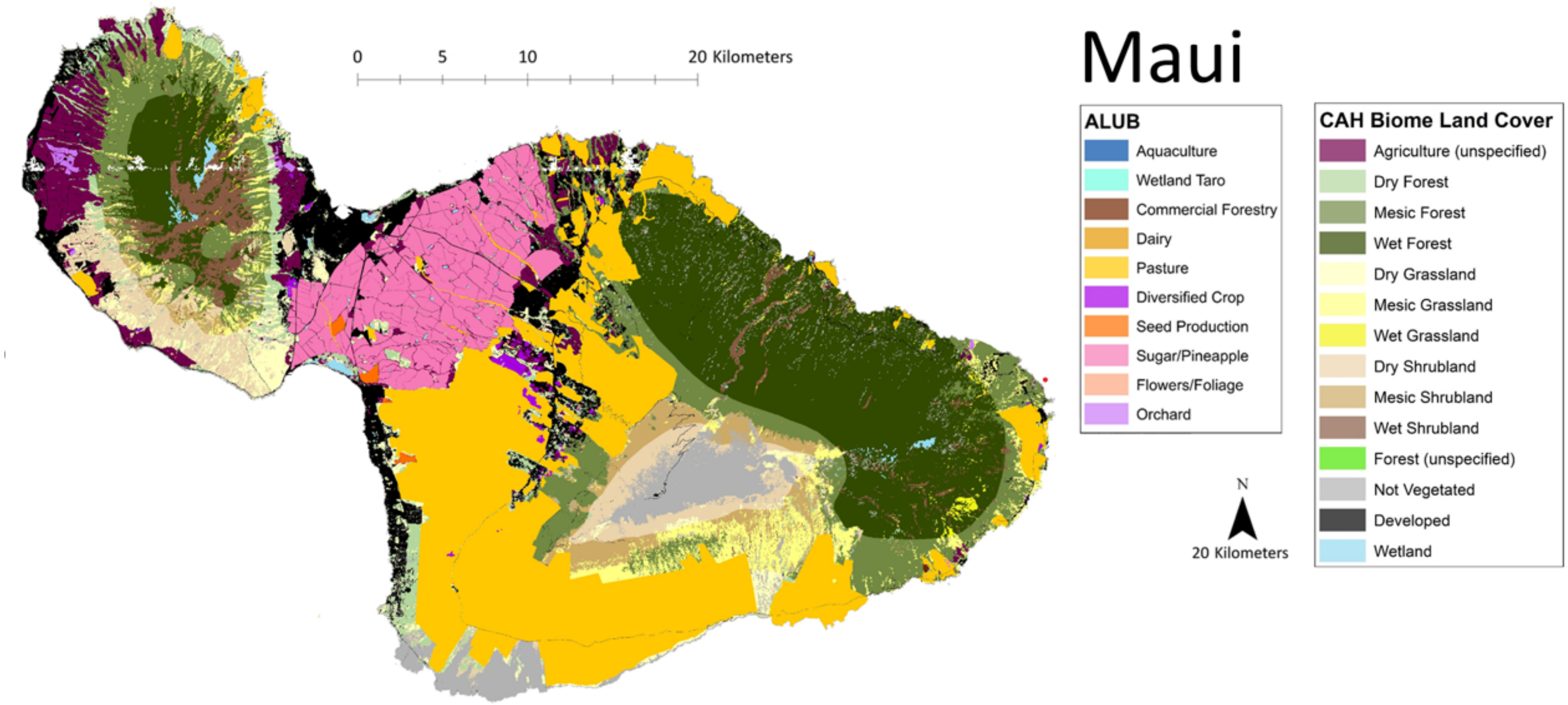

Figure 6. *Maui example of an overlay map of Statewide Agricultural Land Use Baseline (ALUB) and Carbon Assessment of Hawaiʻi (CAH) land cover data layers. ALUB is overlaid over CAH. ALUB is displaying "crop category" and CAH is displaying "land cover by biome."*

The general land cover classification semantics used between HSH, CAH, and ALUB vary (Table 8). Furthermore, there is a vast range in accuracy and land use classification coverage between the three land use data layers we used (Fig. 7). Our HSH land cover data collected between 2017-2020 is the most accurate and up-to-date but has sparse coverage. ALUB includes data from 2011-2015, was co-produced with stakeholders, and only has coverage for agricultural lands. CAH is a wall-to-wall land use map, including natural and working land data up to 2014; however, the classifications are not all verified by stakeholders and land owners, but rather by high-resolution imagery. Because CAH is wall-to-wall coverage and ALUB is not, there are areas across the islands that have data for CAH and no data for ALUB.

Table 8. General land cover classifications for the Hawaiʻi Soil Health (HSH), Agricultural Land Use Baseline (ALUB) and Carbon Assessment of Hawaiʻi (CAH) land cover data layers.

HSH land cover categories	ALUB categories	CAH land cover categories (major)
Agroforestry	Diversified crop	Agriculture
City/state park	Seed production	Grassland
Cropland	Sugar/pineapple	Shrubland
Managed forest	Flowers/foliage	Forest
Orchard	Orchard	Other
Pasture	Dairy	Not vegetated
Protected forest	Pasture	Developed
Residential	Commercial forestry	Wetland
Unmanaged/Abandoned	Wetland taro	
	Aquaculture	

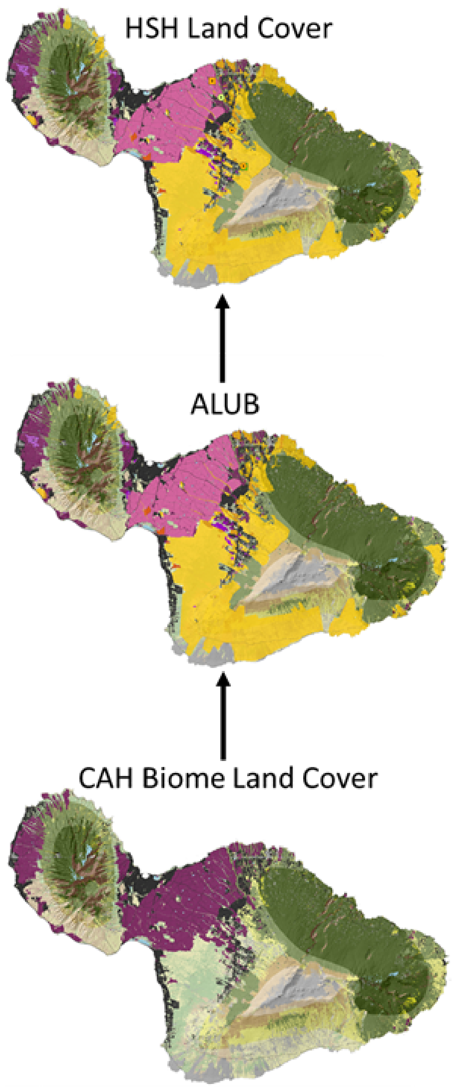

Figure 7. *Visualization of land cover data coverage and accuracy between the Hawai‘i Soil Health (HSH) sites, Agricultural Land Use Baseline (ALUB), and Carbon Assessment of Hawai‘i (CAH). ALUB is spatially explicit polygons of agricultural land coverage, and was produced with stakeholders in 2015. It does not include land classification for non-working lands. CAH is wall-to-wall map coverage. It was created by updating existing land cover data layers up to 2014, and using high resolution imagery. It includes working and natural lands, but is largely not verified by land owners.*

Critical gaps in land use cover. We identified five different types of inconsistencies between the HSH, ALUB, and CAH land cover data (Fig. 8). From the spatially joined CAH and ALUB layer we selected data using two different methods to identify inconsistencies in land use/cover classifications. 1. Select by Attribute: CAH – agriculture, ALUB – no data; "major_LC" = 'agriculture' AND "CropCatego" = ' '. 2. Select by Attribute: CAH – not agriculture, ALUB – any agriculture data; "major_LC" <> 'agriculture' AND "CropCatego" <> ' '. Utilizing the selections for visualisation, we created polygon outlines of the areas that are inconsistent between data layers. (Fig. 8). Next, we compared the land cover data collected at our HSH sites to the CAH and ALUB data layers. We examined each site point and identified which were inconsistent with CAH and/or ALUB. There were three general types of conflicts: 1. HSH was in conflict with CAH, 2. HSH was in conflict with ALUB, and 3. HSH was in conflict with both CAH and ALUB (Fig. 8). Because the land cover classifications between HSH, CAH, and ALUB are different, the inconsistency types were kept general at this stage until we are able to reclassify land cover types with stakeholders and landowners. The inconsistency shapefiles can be downloaded from the **gaplandcov** folder included, and PDF maps with the inconsistency polygons overlaid the joined CAH-ALUB land use layer can be downloaded from the **TMK_ConflictMaps** folder included.

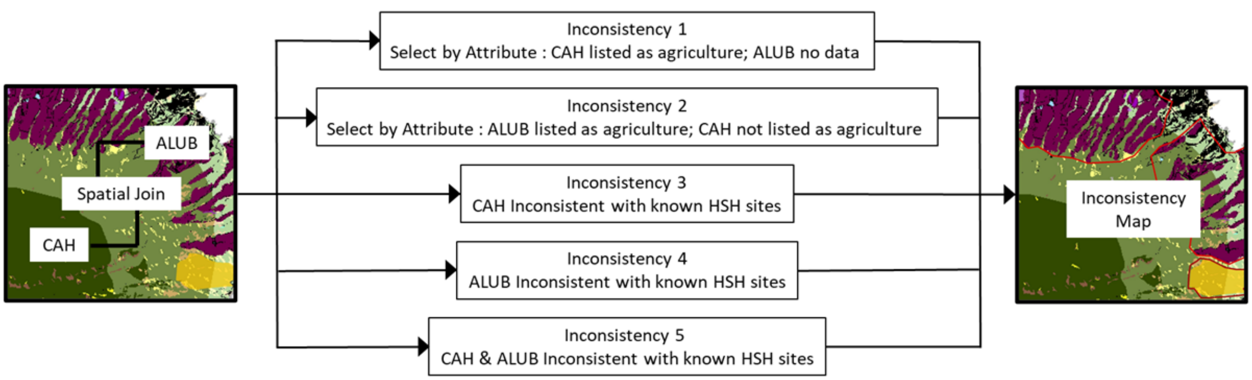

Figure 8. *General workflow for analysis of the Carbon Assessment of Hawai'i (CAH) land cover, Statewide Agriculture Land Use Baseline (ALUB), and Hawai'i Soil Health (HSH) land cover data layers to identify inconsistencies between land cover classification. The resulting inconsistency map will be used to focus on areas that need to be updated.*

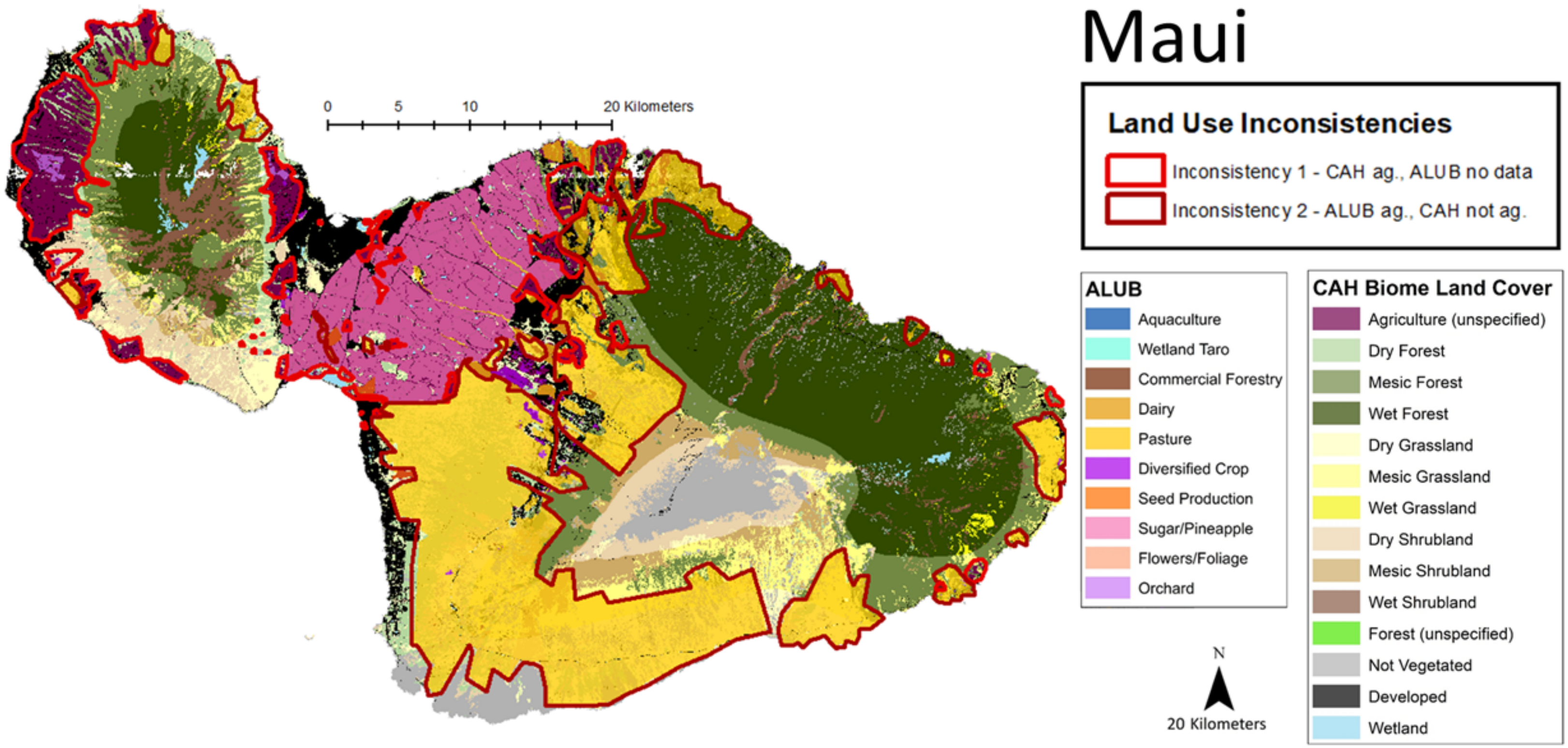

Figure 9. *Maui example with outlined areas of land use classification inconsistencies between the Carbon Assessment of Hawai'i (CAH) land cover and Statewide Agriculture Land Use Baseline (ALUB) data layers.*

Overall, CAH had larger extents of general agricultural lands than mapped by ALUB, but it did not classify most pasture areas as agriculture. ALUB included a larger range of pasture lands, was more specific about agricultural type, but did not discriminate between developed areas (roads, structures, etc.). When not including pasture lands, ALUB showed agricultural lands were abandoned when compared to CAH. The HSH showed some ALUB agricultural lands were abandoned and left unmanaged. Additionally, it revealed the nuanced nature of pasture lands, grasslands, and forests.

4. Soil Health Measurements to Fill Gaps

Overview. From the University of Hawai‘i's recent survey of natural and working lands in Hawai‘i (see Hubanks, 2019) (Fig. 10, 11) key soil health indicators were selected from an initial suite of 46 parameters known to link with dynamic biological, chemical, and physical soil properties (Crow et al. in preparation) (Fig. 11). Key components of soil health, including land use history (specifically intensive monocrop agriculture), current land use practices, and broad mineralogical classification (high activity clays or HAC, low activity clays or LAC, or poorly and non-crystalline minerals or PNCM), must be understood and integrated into the development of a soil health index, which should set minimum and maximum benchmarks and weight parameters according to relevant and fair standards. In turn, the state of each driver must be ascertained and recorded in databases designed for syntheses of soil health into the future (see Box 5 for more details).

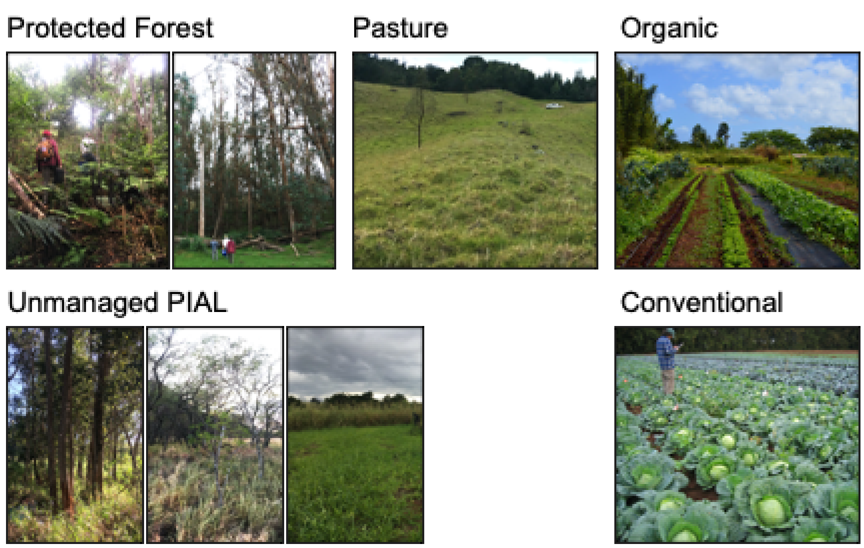

Figure 10. *Five land use classifications were the focus of the original survey used to select the proposal soil health parameters for Hawai‘i. These included protected forests (native and non-native), pastures, unmanaged previously intensive agricultural lands (UPIAL), and intensive croplands (both organic and conventional) (adapted from Hubanks 2019).*

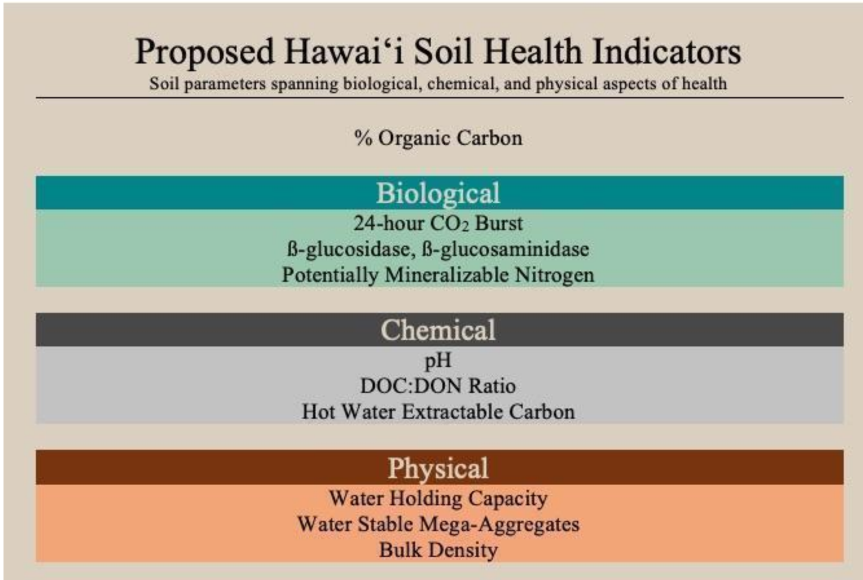

Figure 11*. Each of these parameters link directly to critical functions that soils play in ecosystem C, nutrient, energy, and water flows. These soil functions are tied to human well-being through ecosystem services that collectively build resilience into landscapes and communities. These ecosystem services tie directly to global and local sustainable development goals such as those on the Aloha + Challenge, a statewide public-private commitment to achieve Hawai‘i's social, economic, and environmental goals by 2030 (Adapted from Hubanks 2019).*

Data Collection. The Hawai‘i soil health analyses were conducted at key sites with attributes that contribute to coverage of data resources across the range of natural and working lands in Hawai‘i. There were 14 sites, each with a cluster of 3-4 within-site samples, for a total of 47 sample analyses completed. These sites fall under two categories based on whether the site partners have a plan for **land use change** (i.e., sites where we may return for future sampling to detect change) (Sites A1-7, 26 samples) or represent key **benchmarks** (i.e., long-term systems that serve as an indicator for stable soil health status) (Sites B8-14, 21 samples).

A. **Land use change**. Samples collected in the underlined land use.

1. <u>Unmanaged</u> to organic agriculture, Oxisols: Anonymous partners - 1 site, 3 reps (3 samples total)
2. <u>Protected forest, non-native</u> to agroforestry, Ultisols: Kākoʻo ʻŌiwi - 1 site, 3 reps (3 samples total)
3. <u>Organic agriculture</u> to soil health management, Vertisol: Kahumana Organic Farm, reduced N input, 1 site, 4 reps (4 samples total)
4. <u>Conventional agriculture</u> to soil health management: Tolentino Farm, Vertisol, compost and cover crops, 1 site, 4 reps (4 samples total)
5. <u>Conventional agriculture</u> to soil health management: Twin Bridges Farm, Oxisol and Mollisol, compost and cover crops, 1 site, 4 reps (4 samples total)

6. Organic or conventional agriculture to soil health management: Aloun Farms, Oxisol and Vertisol, compost and biosolids, 1 site, 4 reps (4 samples total)
7. Organic agriculture to soil health management: MA‘O Organic Farm, Vertisol, cover crops, 1 site, 4 reps (4 samples total)

B. **Benchmarks**. Samples represent a potential benchmark for soil health for that soil order under a long-term land use. Samples were provided by partners at the Center for Microbiome Analysis through Island Knowledge, the Institute C-MĀIKI https://www.c-maiki.org . UPIAL refers to unmanaged previous intensive agricultural lands.

8. CM-7 - Protected Forest, Oxisol, 1 site, 3 reps (3 samples total)
9. CM-5 - UPIAL/Forest, Oxisol, 1 site, 3 reps (3 samples total)
10. CM-3 - UPIAL/Forest, Oxisol, 1 site, 3 reps (3 samples total)
11. CM-2 - UPIAL/Forest, Mollisol, 1 site, 3 reps (3 samples total)
12. CM-1 - UPIAL/Forest, Mollisol, 1 site, 3 reps (3 samples total)
13. CM-4 - Floodplain/Woody shrubs, Inceptisol, 1 site, 3 reps (3 samples total)
14. CM-6 - Beach/Woody shrubs, Sand, 1 site, 3 reps (3 samples total)

Results.

Table 9. Summary table showing mean ± *one standard error* values for each soil health parameter at each site. Units for each parameter may be found in the table above.

Site	PIAL.	Current LU	Min-erals	%OC	CO_2 burst	B gluc	B gl.am	PMN	pH	DOC: DON	HW EC	WHC	mega-WSA	BD
1	PIAL	UPIAL	LAC	2.67	73.60	49.79	44.72	24.78	5.29	116.70	91.0	77.08	7.89	1.10
				0.23	*15.16*	*11.44*	*7.17*	*6.22*	*0.10*	*22.56*	*20.6*	*1.66*	*0.75*	
2	none	ProFor	LAC	6.68	371.26	94.16	60.96	175.92	7.22	13.27	1,223.	130.24	13.41	1.05
				1.24	*68.71*	*19.27*	*7.96*	*51.61*	*0.11*	*1.74*	*261.4*	*7.28*	*1.38*	
3	none	OrgCrop	HAC	1.20	63.40	79.83	20.43	8.45	7.77	7.80	279.2	100.21	1.71	0.85
				0.14	*4.63*	*2.84*	*1.88*	*1.79*	*0.16*	*0.13*	*53.5*	*5.52*	*0.55*	
4	PIAL	ConvCro	HAC	1.54	45.73	30.06	10.75	6.08	7.01	19.66	321.3	89.56	1.50	1.00
				0.10	*6.92*	*3.48*	*1.51*	*1.20*	*0.34*	*11.29*	*62.8*	*1.01*	*0.17*	
5	PIAL	ConvCro	HAC	2.23	34.33	24.84	8.80	4.73	6.48	11.98	241.1	79.94	1.44	0.90
				0.13	*1.12*	*5.28*	*0.93*	*1.26*	*0.03*	*16.19*	*25.1*	*2.36*	*0.78*	
6	PIAL	ConvCro	HAC	1.42	15.75	31.51	14.96	0.77	8.14	17.69	117.0	77.19	2.50	1.10
				0.02	*1.63*	*6.18*	*2.38*	*0.77*	*0.10*	*6.08*	*38.7*	*2.53*	*1.71*	

7	none	OrgCrop	HAC	1.22	18.98	56.00	15.38	2.48	7.42	11.26	146.3	75.66	6.14	0.80
				0.17	2.97	3.39	1.60	1.01	0.18	1.79	19.1	4.78	3.28	
8	none	ProFor	LAC	15.16	133.16	40.99	19.90	78.79	5.15	88.84	1,172	129.50	39.66	1.10
				0.74	10.90	4.03	1.52	24.24	0.07	4.49	160.4	4.56	11.46	
9	PIAL	UPIAL	LAC	10.04	405.27	109.45	78.32	124.28	7.64	159.19	1,286	104.94	10.16	1.10
				1.38	47.14	14.77	7.71	64.78	0.28	29.89	337.0	6.30	1.35	
10	PIAL	UPIAL	LAC	7.86	371.20	86.49	70.09	111.55	6.91	113.06	454.2	107.40	7.95	1.10
				0.27	47.38	18.16	11.19	12.82	0.17	4.51	172.0	5.15	0.93	
11	PIAL	UPIAL	HAC	6.09	307.59	106.91	81.85	104.17	7.88	158.94	600.2	84.69	14.21	1.25
				0.50	44.03	10.31	2.52	50.67	0.03	27.39	231.0	2.09	4.79	
12	PIAL	UPIAL	HAC	10.39	69.95	85.12	61.31	29.12	5.89	47.34	155.3	133.61	11.38	1.25
				1.77	28.64	16.02	12.51	10.23	0.13	14.73	94.8	7.04	0.99	
13	none	floodpl	HAC	6.62	309.69	74.31	60.82	95.37	6.97	101.41	350.1	117.54	21.01	1.13
				3.36	50.06	8.68	7.17	17.63	0.47	1.70	63.6	9.36	9.46	
14	N	beach	Sand	25.88	49.04	62.62	44.67	21.87	7.91	135.43	147.5	42.00	0.59	1.48
				12.37	18.92	17.87	9.83	8.21	0.38	29.43	68.9	7.81	0.22	

PIAL = Previous intensive agricultural lands, current LU = current land use, UPIAL = unmanaged previous intensive agricultural lands, ProFor = protected forest, OrgCrop = organic cropland, ConvCro = conventional cropland, floodpl = floodplain, LAC = low activity clays, HAC = high activity clays, %OC = total organic carbon, B gluc = B-glucosidase, B gl.am = B-glucosaminidase, PMN = potentially mineralizable nitrogen, DOC:DON = ratio of dissolved organic carbon to dissolved organic nitrogen, HWEC = hot water extractable carbon, mega-WSA = mega-size class water stable aggregates, BD = bulk density.

Until a soil health index is created for Hawai‘i that takes into consideration limitations due to past land use, current land use, and mineralogy, these values may be considered relative to other sites with similar characteristics. A summary table showing means from the initial survey of 66 sites across the Hawaiian islands (adapted from Hubanks, 2019) is provided below from Crow et al. (in preparation) for comparison to the reported values.

Table 10. Data summary from Crow et al. (in preparation), adapted from Hubanks 2019 for comparing the current database values to the contracted data collected.

	Min	Max	Mean	Median	None n=27	PIAL n=39	Protected Forests n= 9	Pasture n=12	Unmgd PIAL n=15	Organic Cropland n=12	Conv Cropland n=18
%OC	0.83	32.5	5.73	2.33	11.0 ± 3.34*	2.10 ± 0.39*	18.5 ± 7.84[a]	8.58 ± 3.55[ab]	2.20 ± 0.15[b]	3.09 ± 0.91[ab]	2.12 ± 1.25[b]
CO_2 Burst	13.3	527.1	102.6	51.4	195.2 ± 50.79*	37.2 ± 5.22*	274.5 ± 126.7[a]	177.8 ± 69.5[ab]	52.1 ± 8.87[ab]	69.5 ± 19.0[ab]	30.5 ± 8.67[b]
β-Gluc	20.7	230.5	92.1	83.8	119.5 ± 18.24	72.3 ± 12.4	117.3 ± 32.2[ab]	131.1 ± 37.6[ab]	113.6 ± 18.9[a]	78.2 ± 9.86[ab]	44.9 ± 14.6[b]
β-Glucmin	7.71	134.1	47.6	39.0	77.5 ± 12.8*	27.7 ± 4.72*	81.3 ± 26.4[a]	90.9 ± 19.9[a]	44.52 ± 5.31[a]	33.6 ± 7.15[ab]	13.9 ± 2.13[b]
PMN	0.00	304.8	41.1	20.3	83.7 ± 28.7*	11.6 ± 2.88*	152.8 ± 76.2[a]	54.3 ± 15.1[ab]	21.7 ± 3.48[abc]	23.2 ± 8.67[bc]	4.70 ± 2.79[c]
pH	3.71	7.86	6.44	6.7	6.43 ± 0.39	6.42 ± 0.26	6.04 ± 1.17	6.51 ± 0.32	6.21 ± 0.39	7.13 ± 0.27	6.32 ± 0.57
DOC:DON	2.03	808.9	169.1	38.0	94.1 ± 89.4	203.0 ± 51.6	2.68 ± 0.45	17.0 ± 13.9	169.5 ± 110.8	313.7 ± 191.9	257.0 ± 73.3
HWEC	48.4	13,400	1096.5	331.6	2378.1 ± 1390.7*	197.3 ± 29.8*	5245.0 ± 4085.6[a]	1001.1 ± 444.0[ab]	297.2 ± 27.1[ab]	466.3 ± 143.0[ab]	172.0 ± 59.1[b]
WHC	56.7	208.5	85.2	69.2	108.5 ± 16.7	69.7 ± 2.14	136.7 ± 40.3	97.9 ± 23.8	67.4 ± 2.49	76.0 ± 5.37	72.0 ± 5.6
%WSAmega	0.00	96.9	96.9	47.1	67.4 ± 11.0	29.5 ± 8.54	73.2 ± 15.0	79.9 ± 12.7	46.4 ± 14.9	29.6 ± 15.7	24.4 ± 18.2
BD	0.22	1.19	0.84	0.91	0.69 ± 0.10	0.94 ± 0.05	0.54 ± 0.20	0.80 ± 0.20	1.01 ± 0.04	0.86 ± 0.03	0.85 ± 0.11

PIAL = previously intensive agricultural lands; None = no plantation history; %OC = Total organic carbon; β-Gluc = ß-glucosidase; β-Glucmin = ß-glucosaminidase; PMN = Potentially mineralizable nitrogen; DOC:DON = DOC to DON ratio ; HWEC = Hot water extractable carbon; WHC = water holding capacity; %WSAmega = Water stable mega-aggregates; BD = bulk density; Unmgd = Unmanaged; Conv = Conventional

For example, site 2 was a protected forest, with non-native species about to undergo biocultural restoration into multistrata agroforestry at Kāko‘o ‘Ōiwi within the He‘eia National Estuarine Research Reserve (NERR) (Melone et al., 2021). There was no previous intensive land use history, so the values may be most directly compared to the “none” and “protected Forests” columns in the table. Compared to the average database values for the other “none” sites without previous intensive cultivation, the Kāko‘o ‘Ōiwi site was lower for %OC, enzymes, DOC:DON, HWEC, WHC, and %WSAmega and higher for CO_2 burst, PMN, and BD. Compared to the average database values for the other “Protected Forest” sites, the Kāko‘o ‘Ōiwi site was lower for %OC, enzymes, HWEC, %WSAmega and higher for CO_2 burst, pH, PMN, DOC:DON, and BD. Because for some of these indicators, higher is better and for others, lower is better (and some, there is an optimum), the need for an index that weights each parameter according to its relevant benchmarks and normalizes each parameter to an ideal value is imperative for making fair assessments over time.

Box 5. The Hawai‘i Soil Health Tool. The Hawai‘i Soil Health Tool is a web-based portal for soil health information and requesting soil health testing as part of ongoing research projects (Fig. 12). What is the connection between climate and soil health? Soil organic matter and its C content is the central link between climate regulation and soil health. Carbon comprises approximately one half of soil organic matter, which is critical to many soil functions that affect the balance and flow of water, nutrients, and energy through the soil ecosystem. Carbon is also in CO_2 and CH_4 two of the most influential greenhouse gases that are forcing our atmosphere into a warmer, more extreme climate state. Metrics of soil health, which include key biological, chemical, and physical parameters, are connected to ecosystem services through functional roles (such as erosion control, C storage, nutrient transformation, water filtration, and gas exchange).

Land use and management practices that promote soil organic matter retention therefore also promote climate regulation through C sequestration and/or storage, as well as healthy soil systems. Soil health initiatives are ongoing at national and international levels (Jian et al., 2020) but have struggled to link improvements in soil health to yield and profit and much ongoing work aims to do just that (Amelung et al., 2020). However, the value of maintained or improved soil health is much greater than just economic return directly related to yield and other input-driven savings such as reduced fertilizers and water requirements. Increasingly, soil health is linked to a vast array of other ecosystem services that encompass somewhat better the natural and social capital humans derive from improved soil functions as a result of healthy soils (Lehmann et al., 2020). From this, we understand that healthy soils and healthy societies are intertwined. Healthy soils are increasingly linked to healthy societies (Amundson et al., 2015), thus directly supporting a number of sustainability goals (Adhikari and Hartemink, 2016).

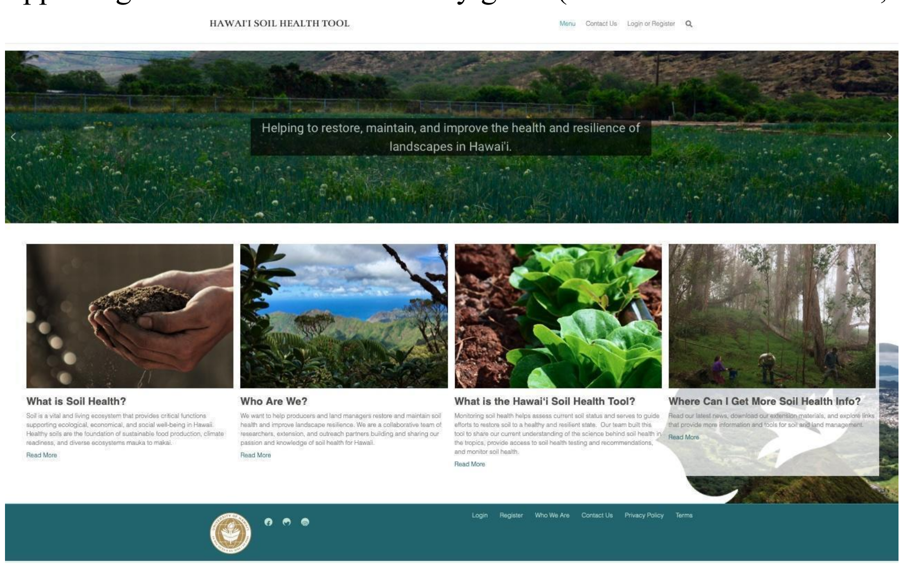

Figure 12. Additional information about the Hawai‘i Soil Health test is available at Hawai‘i Soil Health Tool https://soilhealthhawaii.org.

5. Summary

Data gaps in Hawai‘i GHG emission and soil C storage inventories have been identified across natural and working lands. Improved benchmarking and developing an equitable soil health index for Hawai‘i’s diverse natural and working lands is only possible with additional data resources. As more data are available in the coming years, an index that summarizes the soil health of a site in one number will become available for monitoring change over time. Currently, presented data establishes a benchmark and demonstrates the potential of natural lands and working lands as a diversified landscape to increase soil regulating services in the landscape, soil C, and supports Hawai‘i food security. It is vital to understand the critical role of efficient nutrient management and soil conservation practices in working lands to reduce GHG emission and C footprint. It is relevant to emphasize the life cycle analysis of the working lands, considering the footprint and co-benefits, such as soil C sequestration potential, control of biomass, reduced wildfires, increased local food production, and boost in the local economy. Similarly, it is imperative to remember natural lands’ role in clean air and water, biodiversity, wildlife habitat, and cultural resources. Then, it will be possible to comprehend large-scale assessments of natural and working lands climate mitigation and landscape preservation potentials by filling the inventory gaps accurately. Finally, across Hawai‘i natural and working lands, spatial planning and landscape optimization approaches should consider total soil C sequestration potential and co-benefits such as soil ecosystem services and food security.

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