DRAFT Final Report (Draft 05/05/2021 for GHGSTF review)

State of Hawaiʻi Office of Planning
Working Lands Baseline and Benchmarks

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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.

The original **scope of work** 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 for soil GHG flux, soil carbon (C) stocks, and cross- sectoral public GIS layers for land use are available at the following permanent links in ScholarSpace, the University of Hawaiʻi's open-access digital repository.

Paste link to GHG
Paste link to soil C

The soil health data **collection** is available in ScholarSpace.

Paste link to soil health dataset

This report provides an index of references included in the data compilations found at the links above and discusses the known and studied sources of soil GHG flux and C storage and sequestration of Hawaiʻi'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 benchmark and baseline assessment for Hawaii's natural and working lands that comprise the agricultural, forestry and other land uses (AFOLU) sector. Finally, we align our current state of knowledge with the U.S. Climate Alliance's pipeline development approach to identify ready to go projects for building climate resilience in natural and working lands.

Executive Summary

Key findings for natural and working lands in Hawai‘i

[Section 1 GHG flux, data compilation and discussion].

[Data compilation]

Table 1. Index of known references for GHG data in Hawai‘i’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 (what crop?)	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

Additional GHG assessments include Miller et al. (1997), Konan and Chan (2010), and State of Hawaii Department of Health (2019). 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. Considering during the 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 was 11,548 and 9,303 tons, respectively.

Konan and Chan (2010) studied the direct and indirect GHG from Hawaiʻiʻs economic sectors; Table 2 includes GHG emissions from the crops and animals industry sectors in Hawaiʻi. Results indicated the crops and animal sectors are some of the least impacted sectors by tourism in Hawaiʻi. 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 Hawaiʻi natural and working lands.

Table 2 Direct and indirect greenhouse gas emissions by final demand (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

The State of Hawaiʻi Department of Health (2019) reported the AFOLU sector contributes 1.10 MMT CO_2-eq. during 2015; which constitute 5.2% of total Hawaii GHG emissions. The main sources of GHG from Hawaiʻs'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%).

[Highlights of results found in compilation by management system]

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 the 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 carbon, nitrogen, phosphorus availability, and oxygen status. The use of biochar for napiergrass increased yields by 14% and reduces 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 napiergrass than in sweet corn. In the same study Meulemans (2016) reported N_2O emissions from corn were 6 to 17 times higher than in napiergrass. Biergert (2016) reported after biochar application in napiergrass, CO_2 and N_2O emissions are 9.0 kg CO_2-C $ha^{-1}$and 0.24 g N_2O-N ha^{-1}. 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. Available GHG flux from aquaculture systems 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 phosphorus 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 nitrous oxide (N_2O) and nitric oxide (NO) after experimental additions of nitrogen (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° 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 nitrogen in the 300-yr site and by phosphorus 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 Ohi'a Hawaiian tropical forest has caused N-oxide emissions 16-fold since its first occurrence during the past 40 yr (Hall and Asner, 2007). Litton et. al (2008) reported that non native invasive grasses in the understory forest increase C emissions but doesn't affect the total soil C pool.

In more recent research by Holtgrieve (2006) studied the hurricane effects on N trace gas emissions on a rainforest. The N2O 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 hurricane Iniki, during 1992, 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. Other natural land discussed in the literature was peatlands. Chimney et al. (2004) reported deep standing water in the 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.

[Summary of current knowledge for Hawaii]

Pastures. The role of grazed pastures and livestock systems in climate change mitigation has been overlooked in Hawai'i. Current Hawai'i GHG 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 nitrogen (N) in the manure. None of these, nor soil GHG flux, have been directly quantified in Hawaii, to our knowledge.

Fertilizers. The GHG emissions resulting 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 Hawaii, CO_2 main 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.** Similarly in forest, Hall and Matson (1999) reported a critical effect on soil N_2O emission mechanisms due to nitrogen or phosphorus limited forest systems.

[Section 2 Soil C, data compilation and discussion].

[Data compilation]

Table 3. Index of references for soil C data in Hawai‘i natural and working lands.

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 vegetation			Perez, 2001
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., 2004
		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; Funk, 2005; 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 al., 2004; Ares and Fownes, 2001;
		O‘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	Abandoned to	Pasture-	Scowcroft et al., 2004; Idol et al., 2007

lands	forest	abandoned/grassland-koa forest	
	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.
Hawai‘i inventories and reports			Drawdown report 2020

[Highlights of results found in compilation by sector]

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. For example, 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).

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.

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 - 12.7 kg C m^{-2}) in a dry tropical forest in Puʻu Waʻawaʻa. 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 Hawaiʻi Island (Crow et al. 2016).

Grasslands, Shrublands, Forests. See CAH for in depth discussion.

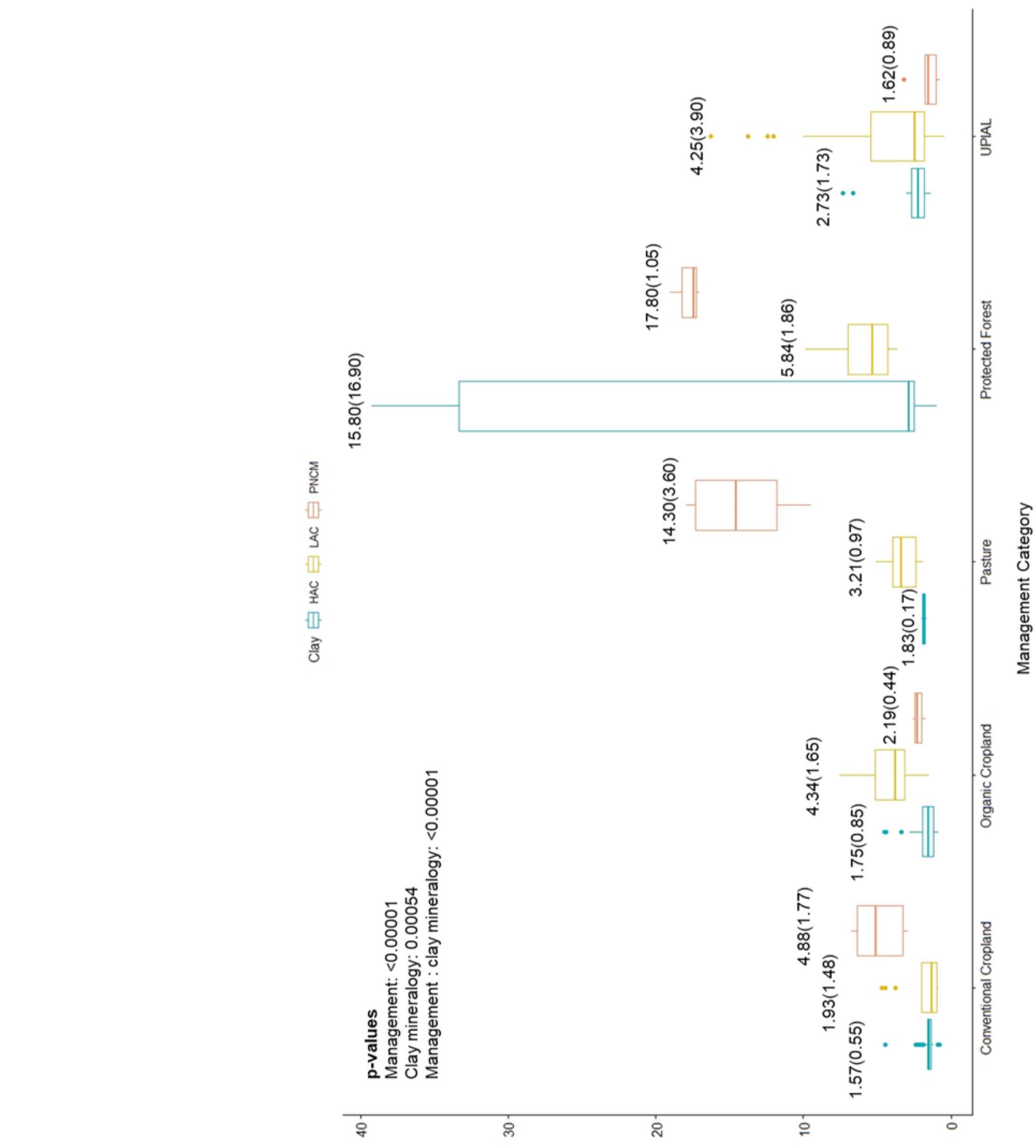
(See box, to be added, for details - Supercharged Hawaiʻi soils).

Converted lands. On Maui, following 120 yr 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 (energycane) 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). 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 yr 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 yr of planting. Similarly, there was no difference in soil C stocks measured to ~ 1 m between paired plots of high quality pasture and 6-10 yr eucalyptus plantation on previous pasture lands along the Hamakua Coast of Hawaiʻi Island (Crow et al. 2016). However, tree plantation resulted in losses of soil C in some high elevation areas (see box, to be added, for details – When reforestation causes C losses). 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 ± 0.8 kg C m^{-2} in approximately 0-80 cm of invaded forest in transition to agroforestry as part of a biocultural restoration on Oʻahu.

(See box, to be added, for details – Rapid improvement for degraded soils).

[Special section - Using the soil C database for summarization]

A summarized output from the database is shown in the figure below. The soil C concentrations (a key component of soil C stocks) are averaged for predominant mineralogy (high activity clay, HAC; low activity clay, LAC; and poorly and non-crystalline minerals, PNCM) and by one of five key current land uses (conventional cropland, organic cropland, pasture, protected forest and unmanaged previously intensive agricultural land, or, UPIAL).


p-values
Management: <0.00001
Clay mineralogy: 0.00054
Management : clay mineralogy: <0.00001
Clay
HAC
LAC
PNCM
1.57(0.55)
1.93(1.48)
4.88(1.77)
1.75(0.85)
4.34(1.65)
2.19(0.44)
1.83(0.17)
3.21(0.97)
14.30(3.60)
15.80(16.90)
5.84(1.86)
17.80(1.05)
2.73(1.73)
4.25(3.90)
1.62(0.89)
Conventional Cropland
Organic Cropland
Pasture
Protected Forest
UPIAL
Management Category
Organic Carbon (%)
0
10
20
30
40

[Special section - Using the soil C database for a soil C resource map]

Soil C resource maps (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. Different soils have varying potential to sequester soil carbon (Lal, 2018). For example, the volcanic ash-derived soils (Andisols) common to Hawaiʻi 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 is a degraded soil, recently abandoned post-plantation that is available for improved agricultural land use and management or reforestation. 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 Hawaiʻi 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 carbon 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 SOC prediction maps, we: 1. calculated soil organic C stocks from measured soil data, 2. calculated C densities sums from 0-30 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. 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 250m resolution, with goals of finer 100m resolution. Additionally, the organic layers of soil are removed from the calculations and models. The maps are 30-70% 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.

The table below shows a summary of the available data used in the figure below.

Table 2: *Compiled data to estimate soil organic carbon (SOC) stocks*

Dataset	**Samples *n***	**Depth information**	**Years measured**
Literature review (papers *n* = 42)	239	varies; data often aggregated	1995-2019
Hawaii Soil Health (unpublished)	146	only 0-15 cm	2017-2020
Unpublished collaborator	10	every 15 cm; 0-100 cm	2019
Unpublished collaborator	66	only 0-20 cm	2019
Unpublished collaborator	30	only 0-15 cm	2019
Unpublished collaborator	21	only 0-15 cm	2018-2019
Unpublished collaborator	1020	every 15 cm; 0-100 cm	2015-2017
Rapid Carbon Assessment (unpublished)	754	by horizon; to ~100 cm	2014
National Cooperative Soil Survey	2,256	by horizon; to ~100 cm	1949-2014
Total	**4909**		

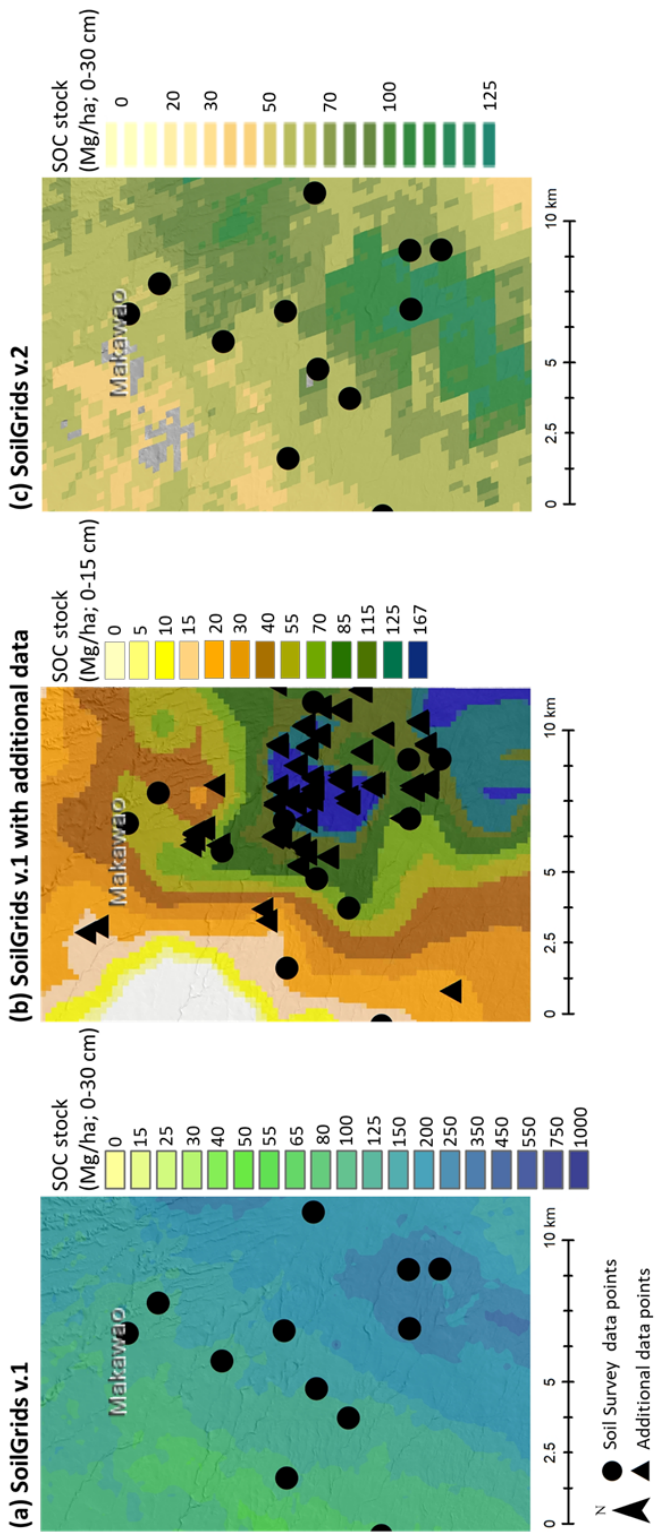


Figure x: Soil organic carbon (SOC) map of Maui at the half-island scale. (a) SoilGrids version 1 – SOC map using only Soil Survey data to a 30 cm depth. (b) SoilGrids version 1 — SOC map using additional compiled measured data. This map only predicts a soil depth of 15 cm. (c) SoilGrids version 2 — SOC map using updated methodology and only Soil Survey data to a 30 cm depth.

While our updates are an improvement, there are still known issues that decrease the accuracy of our soil carbon 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, Hawaiʻi LiDAR and DEMs are not comprehensively wall-to-wall due to cloud coverage, especially in the context of microclimates and topography dynamics. LiDAR and DEMs available for Hawaiʻi are also 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 carbon stock in finer resolution maps, and to account for deeper depths.

[Section 3 Land use classification GIS layers, data compilation and discussion].

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.

[Layer compilation]

***Table 4:** 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)	Agricultural land use based on WorldView-2 satellite imagery (2011-2013), data provided by landowners and stakeholders, County Real Property Tax and Agricultural Water Use data; verified by site visits and stakeholder meetings.	Spatial Data Analysis and Visualization Lab 2015
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

[Discussion from the compilation]

Spatially explicit land management data helps us understand the spatial characteristics of ecosystem services (i.e., C sequestration), especially at the landscape-scale (Fisher et al., 2009; Liao et al., 2020). By having an updated, spatially explicit land use/cover map, we can prioritize areas that enhance ecological outcomes (e.g., C sequestration) by identifying areas of greatest management potential or areas that may be degraded, such as abandoned lands (Fisher et al., 2009; Metzger and Brancalion, 2016).

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 3. The ALUB was not included in CAH and was made in collaboration with stakeholders and landowners — thus assumed to be the most accurate. We spatially joined CAH and ALUB using the Overlay Analysis Tool. (Figure 3). All available land use GIS layers for Hawaiʻi (Table 3) were compiled and projected in NAD 83 Zone 4N using ArcGIS 10.4.1 (ESRI, 2020). All datasets in Table 4 can be downloaded from the HI_Landcover_all.zip folder included.

Additionally, we included land cover data from our Hawaiʻi Soil Health (HSH) sites because we have ground-truthed these data and personally work with the land owners and stakeholders (currently, approximately 70 sites). However, the HSH land cover data is currently only point data — further outreach with our stakeholders is needed to create spatially explicit polygons. The general land cover classification semantics used between HSH, CAH, and ALUB vary (Table 4). Furthermore, there is a vast range in accuracy and land use classification coverage between the three land use data layers we used (Figure 4). 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.

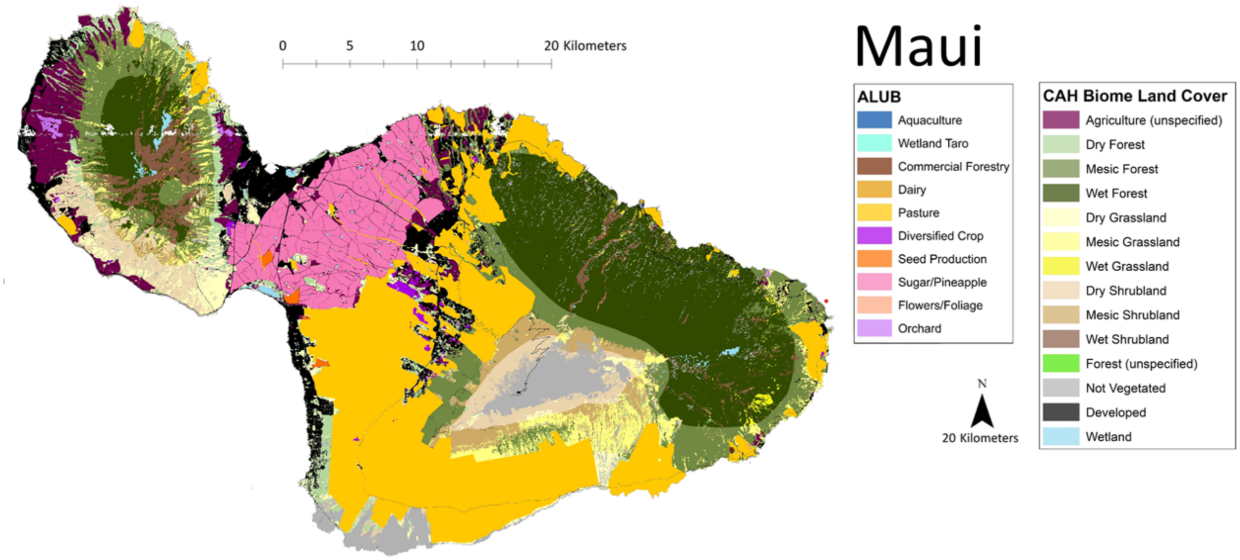


Figure 3. Maui example of joined map of Statewide Agriculture Land Use Baseline (ALUB) and Carbon Assessment of Hawai‘i (CAH) land cover data layers. ALUB is overlaid over CAH. ALUB is displaying “crop category” and CAH is displaying “land cover by biome”.

Table 4: General land cover classifications for the Hawai‘i Soil Health (HSH), Agriculture Land Use Baseline (ALUB) and Carbon Assessment of Hawai‘i (CAH) land cover data layers.

HSH land cover categories	**ALUB categories**	**CAH land cover categories (major)**
Organic cropland	Diversified crop	Agriculture
Conventional cropland	Seed production	Grassland
Pasture	Sugar/pineapple	Shrubland
Unmanaged grassland	Flowers/foliage	Forest
Agroforest	Orchard	Other
Protected forest	Dairy	Not vegetated
Unmanaged forest	Pasture	Developed
	Commercial forestry	Wetland
	Wetland taro	
	Aquaculture	

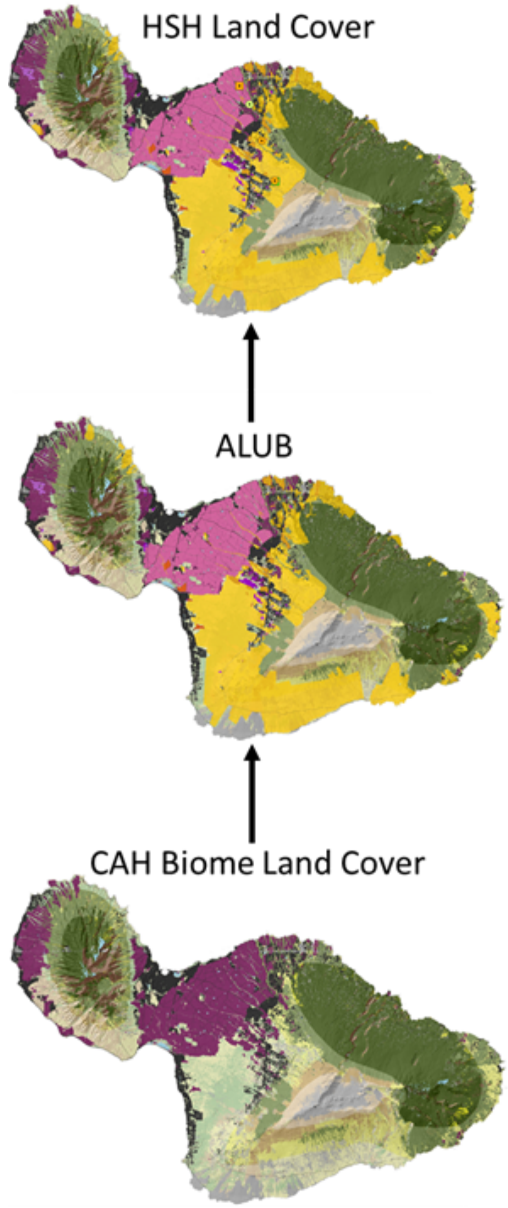


Figure 4: Visualization of land cover data coverage and accuracy between the Hawai'i Soil Health (HSH) sites, Agricultural Land Use Baseline (ALUB), and Carbon Assessment of Hawai'i (CAH). HSH is only point data at select partners' sites, but is the most up-to-date and accurate. ALUB is spatially explicit 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.

[Special section - gaps in land use cover for cross-sectoral]

We identified five different types of inconsistencies between the HSH, ALUB, and CAH land cover data (Figure 5). From the spatially joined CAH and ALUB layer we selected data using two different methods to identify inconsistencies in land use/cover classifications (Figure 5). 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. (Figure 6). 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 (Figure 5). Because the land cover classifications between HSH, CAH, and ALUB are different (Table 4), 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 Landuse_inconsistencyGIS.zip folder included, and PDF maps with the inconsistency polygons overlaid the joined CAH-ALUB land use layer can be downloaded from the Landuse_inconsistencyPDF.zip folder included.

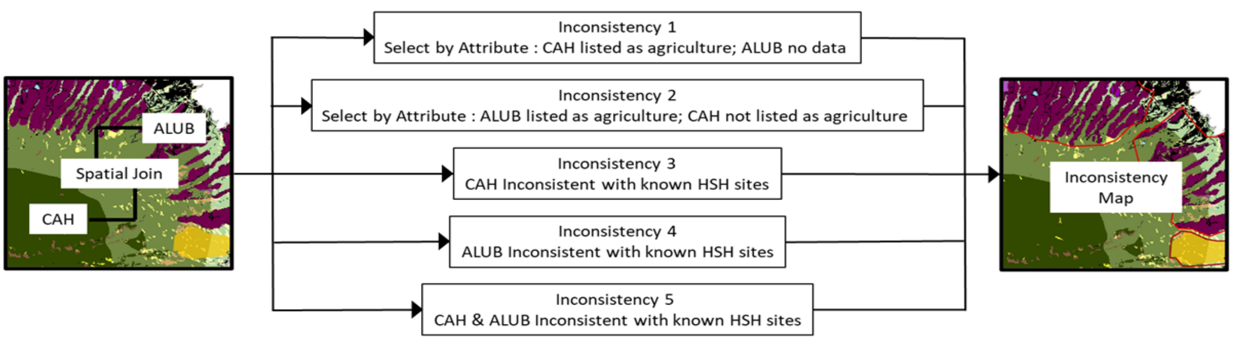


Figure 5: General workflow for analysis of the Carbon Assessment of Hawai‘i (CAH) land cover, Statewide Agriculture Land Use Baseline (ALUB), and Hawai‘i Soil Health (HSH) land cover data layers to identify inconsistencies between land cover classification. The resulting inconsistency map will be used to focus on areas that need to be updated.

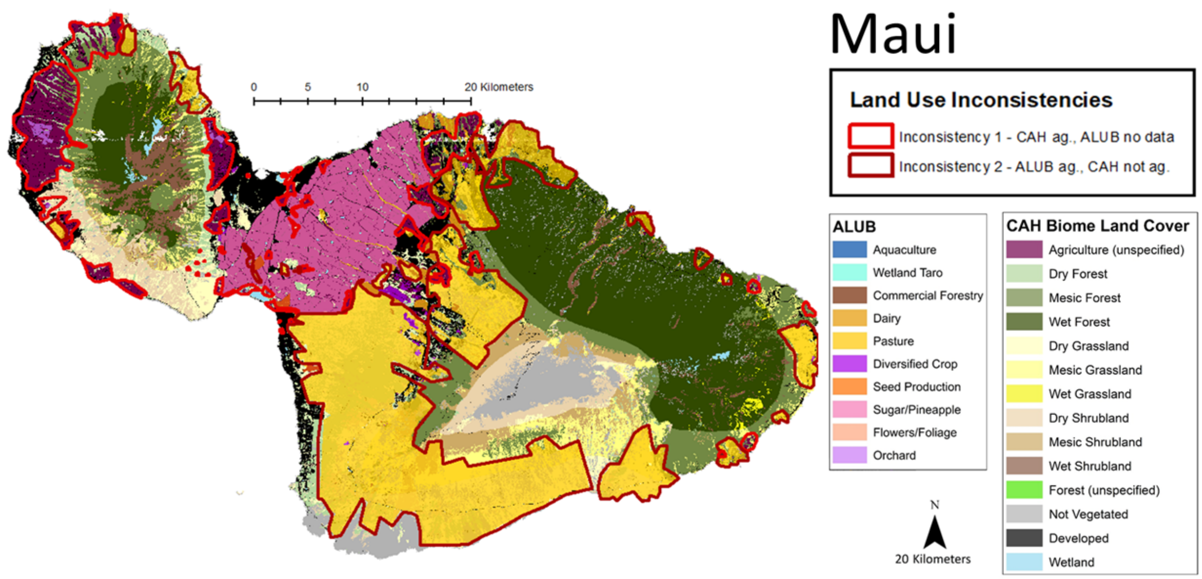


Figure 6. Maui example of outlined areas of land use classification inconsistencies between the Carbon Assessment of Hawai'i (CAH) land cover and Statewide Agriculture Land Use Baseline (ALUB) data layers.

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.

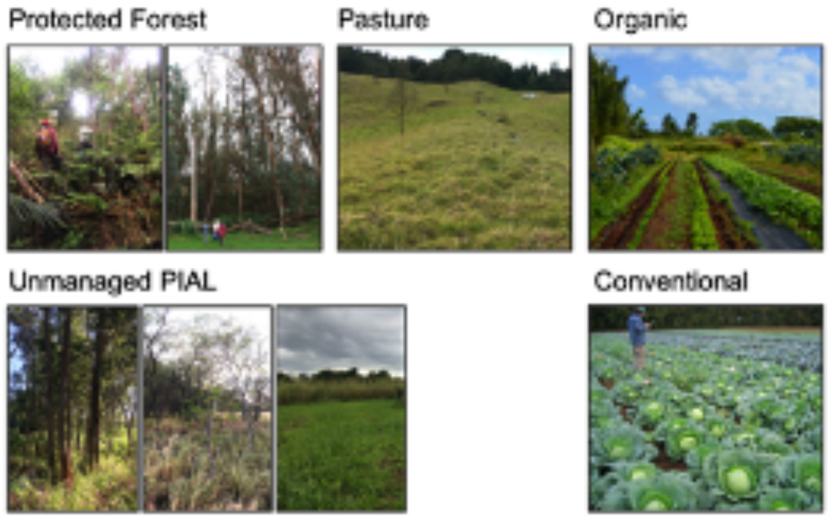
[Section 4 Soil health data collection]

[Overview]

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 (SOM), 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 SOM 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 & Hartemink, 2016).

From the University of Hawaiʻi's recent survey of natural and working lands in Hawaiʻi, 11 key soil health indicators were selected from 46 parameters that declined with long-term intensive cultivation (Fig. below from Crow et al. in preparation) and measured reductions in soil health and soil function tied to losses in SOM due to heavy-tillage and little to no return of organic matter (Hubanks, 2019). Additional information about the Hawaiʻi Soil Health test is available at Hawaiʻi Soil Health Tool https://soilhealthhawaii.org. Key factors determining the benchmarking of soil health are (1) Whether the land was previously under intensive agriculture (in Hawaiʻi, this was likely sugar or pineapple plantation), (2) Current land use and management intensity, and (3) Predominant mineralogy. Therefore, these factors are reported as well.



Proposed Hawai'i Soil Health Indicators

Soil parameters spanning biological, chemical, and physical aspects of health

% Organic Carbon

Biological

24-hour CO_2 Burst
ß-glucosidase, ß-glucosaminidase
Potentially Mineralizable Nitrogen

Chemical

pH
DOC:DON Ratio
Hot Water Extractable Carbon

Physical

Water Holding Capacity
Water Stable Mega-Aggregates
Bulk Density

Each of these parameters link directly to critical functions that soils play in ecosystem carbon, nutrient, energy, and water flows, figure below from Crow et al. in preparation.

Proposed Hawaii Soil Health Indicators	
Parameter	Function and interpretation
Total organic carbon (%)	As the backbone of soil organic matter, a proxy measurement of the amount of soil organic matter; higher value typically relates to benefits of multiple biological, chemical, and physical aspects of soil function
Biological Properties	
24 hr CO_2 burst ($\mu g\ g^{-1}$)	Soil respiration in response to readily available substrate; higher value indicates high microbial activity and high quality organic matter pools
ß-glucosidase (mg p-nitrophenol kg^{-1} soil h^{-1})	Proximate microbial metabolism of amino-containing substrate; higher value indicates nutrient, predominantly N, mineralization
ß-glucosaminidase (mg p-nitrophenol kg^{-1} soil h^{-1})	Potential N supply; higher value indicates bioavailable N forms to support soil productivity
Mineralizable nitrogen ($\mu g\ g^{-1}$)	Potential N supply; higher value indicates bioavailable N forms to support soil productivity
Chemical Properties	
pH	Biological and nutrient availability; 6.0—7.0 is ideal, this is the pH range where plant essential elements are most available, and toxicities are negligible
DOC:DON ratio	Integrated indicator of the balance of organic carbon and organic nitrogen pools; lower is better; higher value indicates disturbance - high DOC indicates available microbial substrate but also potential runoff, priming, and loss if too high, DON is readily broken down by soil microbes into inorganic forms, but low values are associated with N-deposition or poor nutrient management in disturbed systems
Hot water extractable carbon ($\mu g\ g^{-1}$)	Readily available metabolic substrate; higher value indicates soluble organic matter and lysed microbial cells that support microbial activity
Physical Properties	
Water holding capacity (%)	Plant-water relations; higher values indicate improved water storage
Water stable mega-aggregates (%)	Water infiltration, porosity, aeration; higher values improve retention/transport water, promote root growth, provide habitat for microbes, reduce bulk density, and resist erosion
Bulk density (g cm^{-3})	Infiltration, porosity, and rooting environment; lower values indicate soils that are light, aerated, porous, promote root growth, and more workable

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 Hawaiʻi's social, economic, and environmental goals by 2030.

[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 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** (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. Unmanaged to organic agriculture, Oxisols: Anonymous partners - 1 site, 3 reps (3 samples total)
2. Protected forest, non-native to agroforestry, Ultisols: Kāko‘o ‘Ōiwi - 1 site, 3 reps (3 samples total)
3. Organic agriculture to soil health management, Vertisol: Kahumana Organic Farm, reduced nitrogen input, 1 site, 4 reps (4 samples total)
4. Conventional agriculture to soil health management: Tolentino Farm, Vertisol, compost and cover crops, 1 site, 4 reps (4 samples total)
5. Conventional agriculture 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 .

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

[Results]

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. 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, Min = Mineralogy, 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.

Site	PIAL.	Current LU	Min	%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			24.78	5.29	116.70	91.0	77.08	7.89	1.10
				0.23	*15.16*			*6.22*	*0.10*	*22.56*	*20.6*	*1.66*	*0.75*	
2	none	ProFor	LAC	6.68	371.26			175.92	7.22	13.27	1,223.	130.24	13.41	1.05
				1.24	*68.71*			*51.61*	*0.11*	*1.74*	*261.4*	*7.28*	*1.38*	
3	none	OrgCrop	HAC	1.20	63.40			8.45	7.77	7.80	279.2	100.21	1.71	0.85
				0.14	*4.63*			*1.79*	*0.16*	*0.13*	*53.5*	*5.52*	*0.55*	
4	PIAL	ConvCro	HAC	1.54	45.73			6.08	7.01	19.66	321.3	89.56	1.50	1.00
				0.10	*6.92*			*1.20*	*0.34*	*11.29*	*62.8*	*1.01*	*0.17*	
5	PIAL	ConvCro	HAC	2.23	34.33			4.73	6.48	11.98	241.1	79.94	1.44	0.90
				0.13	*1.12*			*1.26*	*0.03*	*16.19*	*25.1*	*2.36*	*0.78*	
6	PIAL	ConvCro	HAC	1.42	15.75			0.77	8.14	17.69	117.0	77.19	2.50	1.10
				0.02	*1.63*			*0.77*	*0.10*	*6.08*	*38.7*	*2.53*	*1.71*	
7	none	OrgCrop	HAC	1.22	18.98			2.48	7.42	11.26	146.3	75.66	6.14	0.80
				0.17	*2.97*			*1.01*	*0.18*	*1.79*	*19.1*	*4.78*	*3.28*	
8	none	ProFor	LAC	15.16	133.16			78.79	5.15	88.84	1,172	129.50	39.66	1.10
				0.74	*10.90*			*24.24*	*0.07*	*4.49*	*160.4*	*4.56*	*11.46*	
9	PIAL	UPIAL	LAC	10.04	405.27			124.28	7.64	159.19	1,286	104.94	10.16	1.10
				1.38	*47.14*			*64.78*	*0.28*	*29.89*	*337.0*	*6.30*	*1.35*	
10	PIAL	UPIAL	LAC	7.86	371.20			111.55	6.91	113.06	454.2	107.40	7.95	1.10
				0.27	*47.38*			*12.82*	*0.17*	*4.51*	*172.0*	*5.15*	*0.93*	
11	PIAL	UPIAL	HAC	6.09	307.59			104.17	7.88	158.94	600.2	84.69	14.21	1.25
				0.50	*44.03*			*50.67*	*0.03*	*27.39*	*231.0*	*2.09*	*4.79*	
12	PIAL	UPIAL	HAC	10.39	69.95			29.12	5.89	47.34	155.3	133.61	11.38	1.25
				1.77	*28.64*			*10.23*	*0.13*	*14.73*	*94.8*	*7.04*	*0.99*	
13	none	floodpl	HAC	6.62	309.69			95.37	6.97	101.41	350.1	117.54	21.01	1.13
				3.36	*50.06*			*17.63*	*0.47*	*1.70*	*63.6*	*9.36*	*9.46*	
14	N	beach	Sand	25.88	49.04			21.87	7.91	135.43	147.5	42.00	0.59	1.48
				12.37	*18.92*			*8.21*	*0.38*	*29.43*	*68.9*	*7.81*	*0.22*	

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 (Hubanks 2019) is provided below from Crow et al. in preparation for reference.

Table 5. Data summary for the proposed key indicators of health for subtropical/tropical and volcanic soils. Significant differences are indicated by * for the past land use (PIAL versus None) comparison and letters for the current land use comparisons. Differences assessed by lsmeans comparison by Tukey's HSD of mixed model with past land use or current land use as a fixed effect and farm/location as a random effect (lmer package).

	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

[Section 5 Discussion]

[Section 5a Identified gaps in available data]

Gaps in knowledge data

- **Greenhouse gas emissions.** 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 compare. 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.

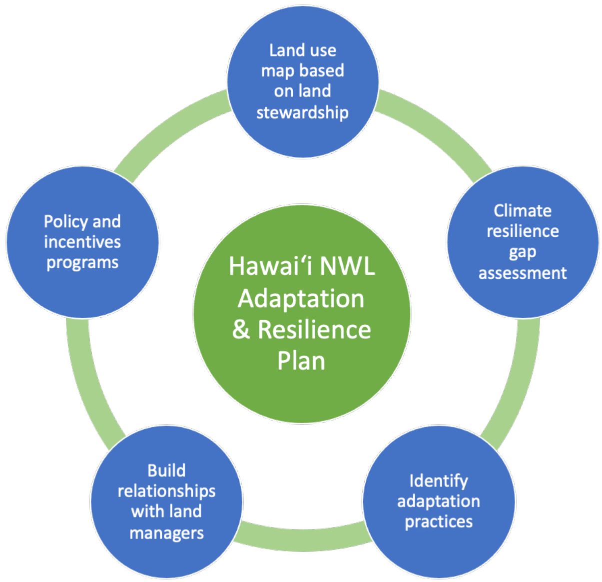
- **Soil C sequestration.** Our study identifies gaps in soil C sequestration rates from vegetable production systems, pastures (meat and dairy industry), agroecosystems, orchard (coffee, macadamia nuts, and other tropical fruits), and recently converted lands (plantation to forest/pastures).

- **Land use classification GIS layers.** Our study identifies inconsistencies in the available Hawaii C assessment, agricultural lands, and the abandoned lands map data layers. More specifically, we identified key known areas in the Island of Maui, and Hawai‘i Island that are missing and could constitute significantly into the C assessment of Hawai‘i natural and working lands. Current efforts from Crow‘s laboratory and the Hawai‘i Natural and Working Lands Research team include an update to the Hawai‘i natural and working lands to create a map tool.

- **Soil Health.** To be summarized.

[Section 5b Pipeline devlopment approach adapted from US Climate Alliance]

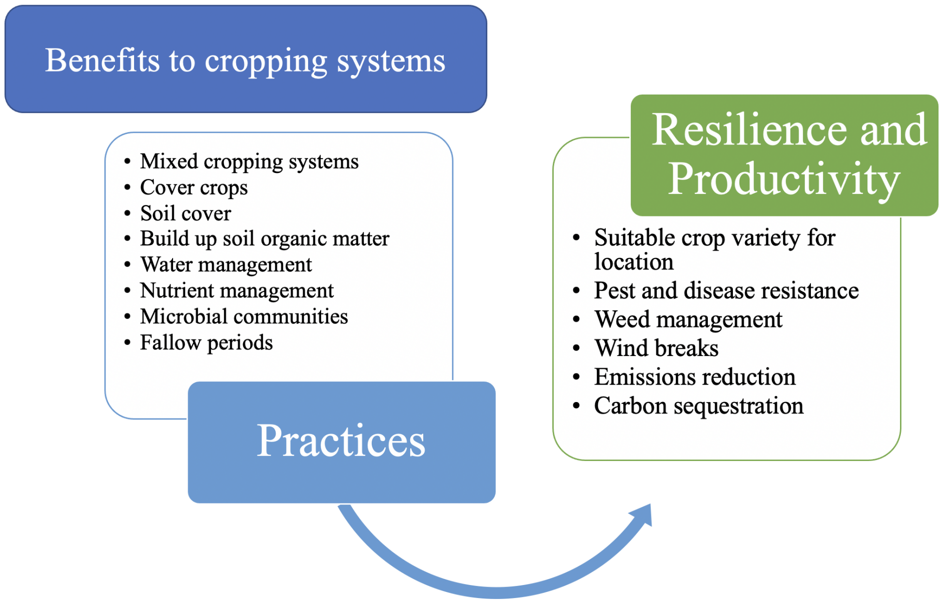
The pipeline development approach suggests "Ready-to-Go" projects requiring resources, funding, and expertise to enable local government, community organizations, and land managers to design and implement climate smart agriculture and forestry projects.



- **Land use map based on land stewardship**
  - Identifying land status and availability.
  - Update Hawaiʻi soil C assessment map abandoned land, and vulnerable lands.
- **Climate resilience gap assessment.** Anticipate the impact of climate variability in the role of natural working lands, and assess vulnerabilities and opportunities.
  - Determine the GHG emissions and soil C sequestration potential of NWL
    - Emissions rate by land use and agricultural practices
    - C sequestration potential by land use and agricultural practices
  - Improving NWL GHG inventories for use in goal setting and policy network.
- **Identify adaptation practices.** Identify the most suitable interventions to preserve and increase natural and working land services. Create a new-generation watershed-scale design plan for effective conservation programs.
- **Build relationships with land managers.** Building relationships with land managers and communities to ensure widespread involvement, climate smart practices implementation, and secure their role in the local economy.
- **Policy and Incentives program.** Craft equitable policy and incentives programs that enable diverse groups to enact natural and working land changes considering climate change projections. That reduces GHG, C sequestration, and the protection of natural resources while meeting local food production goals, biodiversity, watershed protection, and social and cultural values.

[Section 5c Recommended practices in Hawaiʻi by natural and working land sector]

Croplands



Crop adaptation. Crop production adaptation includes the selection of high yielding and drought resistance varieties. This crop characteristics can contribute to a reduction on water and fertilizer use, increase C sequestration, and reduce the expansion to natural lands.

Reduce or no tillage. Mitigation potential of reducing tillage includes a reduction on erosion, by improving soil structure. Also, it provides control to soil aeration, temperature and microbial communities. Economical benefits include a minimize operations costs, time, and labor, Ecological services include soil conservation soil moisture, reduce runoff to aquifers and streams and reduce emissions from land management and N_2O emissions.

Increase soil cover. The increase of soil cover with the use of grasses, legumes, and forbs offer benefits such as weed control, prevent erosion of topsoil, nitrogen fixation and nutrient scavenging, attract beneficial insects and suppress nematodes, and build soil organic matter.

Efficient fertilizer management. An efficient fertilizer management reduces nutrient overload, algal bloom, and potential harm to reef, and reduces N_2O emissions. Economic benefits are the reduced Ag inputs and boost crop yield. Environmentally an efficient nutrient management reduces pressure for deforestation. An efficient fertilizer management system not just reduces nutrient losses and economic investments, but increases crop yields which contributes to reducing imported food and the GHG emissions involved in its process.

Lime application. Lime application is a known practice in Hawaiʻi to increase soil pH. The management of soil pH results in a reduction of N_2O emissions.

Conservation agriculture. Conservation agriculture and regenerative annual cropping solutions increase land resiliency towards climate-related events. Project Drawdown Hawaiʻi defined a regenerative annual cropping solution as any annual cropping system that includes at least four of the following practices: compost application, cover crops, crop rotation, green manures, no-till, or reduced tillage, and organic production. Maaz et al. (Unpublished data, 2020) compiled a list of Natural Resources Conservation NRCS practices (Table 6) that directly improve soil health, and are linked their impacts on increasing carbon inputs and the four SHMS principles of minimizing soil disturbance, maximizing living roots, soil cover and plant or microbial diversity in crop and integrated livestock operations.

Table 6. NRCS conservation practices and their impacts on soil carbon, disturbances, living roots, soil cover, and biodiversity. Areas highlighted in green indicate that the practice of interest has a positive effect on the SHMS principle listed in the column.

<table>
<tr><th>Increase soil carbon</th><th>Minimize soil disturbance (physical, chemical, or biological)</th><th>Maximize living roots</th><th>Maximize soil cover</th><th>Maximize plant or microbial biodiversity</th></tr>
<tr><td></td><td></td><td colspan="3">Cover cropping (Code 340): Grasses, legumes, or mixtures planted for vegetative cover, nutrient cycling, and soil health</td></tr>
<tr><td colspan="5">Conservation cover (Code 327): Establish and maintain permanent vegetative cover for soil health</td></tr>
<tr><td colspan="2">Soil carbon amendment (Code 808): Using carbon-based amendments for soil health

<u>Compatible practices:</u> Nutrient management (Code 590) in order to manage rate, source, placement, and timing of soil amendments and improve soil organic matter.

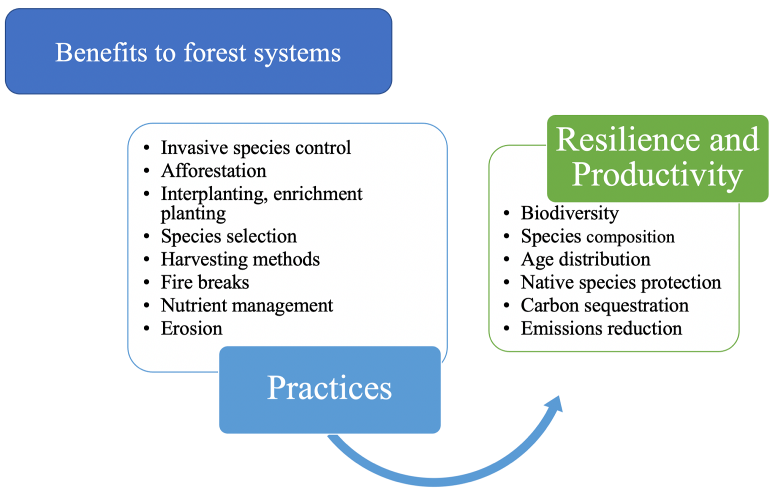
Waste recycling: Microirrigation (Code 441) system to deliver frequent application of small quantities of water on the surface using a pumping plant (Code 533) facility to transfer waster (Code 632) from storage pond for field application

Compost facility (Code 317) structure or device to contain and facilitate an aerobic microbial ecosystem amendment.</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Non-living mulch (Code 484): Plant residues or other suitable materials applied to the land surface to increase soil organic matter

<u>Compatible practice:</u> Tree pruning (Code 660) to remove selected branches and shoots to renew orchard growth and recycle woody material as non-living mulch</td><td></td><td colspan="2"></td></tr>
</table>

		Conservation crop rotation (Code 328) A diversified sequence of crops grown on the same ground (*e.g.*, relay cropping), or crops intercropped together to increase soil health
Alley cropping (Code 311): Orchards alleys planted with agronomic, horticultural crops or forages that produce additional products, increase biodiversity, and enhance soil health		
Tree/Shrub Establishment (Code 612): Establishing woody plants by planting seedlings or cuttings, by direct seeding, and/or through natural regeneration in agroforestry systems to increase soil organic matter, plant diversity, and soil health		
Silvopasture (Code 381): Establishing trees and forages on the same land unit.		

Forests

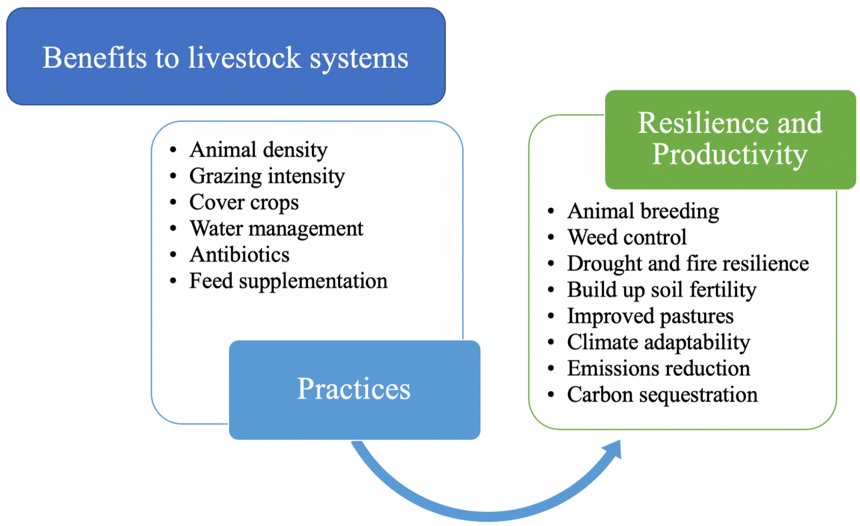


Silvopasture. Silvopasture in tropical systems have the potential to increase by 5.8 times more protein per hectare than the traditional monoculture pasture system, 2.6 times higher stocking rates, reduces CH_4 emissions by 25 to 40%, and increases animal health (Campos Paciullo et al., 2012; Xóchitl and Solorio, 2013; Conant et al., 2017). Environmental include wildlife conservation, nitrogen fixation from legumes, and may reduce the need for chemical fertilization, increase in soil water relations, and promote C sequestration (Murgueitio et al., 2011; Boucher et al., 2012; Montagnini et al., 2013).

Mix production systems and agroforestry. Diversification of agricultural land through agroforestry has a mitigation potential of C sequestration, reducing GHG emissions from soil and fertilizer management, and eliminating emissions from machinery use through a reduction of fossil fuel and energy usage. Environmental co-benefits include the protection of endangered species and increase in biodiversity.

Long rotations. Longer rotations in managed forests between harvests

Grazing lands



Pasture. Bonaudo et al. (2014) summarized principles for managing integrated crop-livestock systems by considering production, immune and metabolic functions, tighten energy cycles with fewer losses, optimized nutrient availability, and landscape management. In tropical and semitropical soils, forage systems face challenging production conditions because the highly weathered soils consist of low natural fertility, low pH, and high Al saturation. However, a study by Blackmore and Vitousek (2000) discussed the co benefits of grazing systems in dry to mesic forest by its role controlling kikuyu grass and therefore reducing wildfires. Across Hawai'i Islands, wildland fires in, mostly shrubland and grasslands, ranged between 5 and 119 km2/yr emitting an average of 0.0942 Tg CO2-eq/yr from 2002 to 2011 (Hawbaker et al., 2017). Under climate smart agriculture, the goal is to achieve high agricultural outputs, regarding quality and quantity, under less input of land, water, nutrients, energy, labor, and capital.

Improved pasture. Sustaining, integrating, and maintaining productive forage cultivars represent a crucial component of ranching systems by its benefits to soil health, drought resiliency, nutrient cycling and recycling, reduction of GHG emissions from the soil and enteric fermentation, and an increase in animal nutrition.

Livestock feeding. Feed forms up to 70% of the cost of animal production. Common forage species were guinea (Panicum maximum), kikuyu grass (Pennisetum clandestinum), Pangola (Digitaria eriantha), and white clover (Trifolium repens).

Animal density and rotation. Essential climate smart practices are focused on the improvement of livestock management through animal feeding, animal density and rotation, and manure management. Livestock feeding, animal genetics and improved forages are vital in reducing enteric fermentation, reducing GHG emissions, and increasing drought resiliency and soil health. The manure management mitigation potential includes waste prevention, reduction of emissions, air quality improvement, and the boost crop yields when used as fertilizer. Increase soil structure and C content, and increase soil water retention. Controlling animal density and rotation reduces soil nutrient hotspots which minimize nutrient losses and GHG emissions.

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