TOWARDS A HAWAI‘I SOIL HEALTH INDEX:
IDENTIFYING SENSITIVE AND PRACTICAL INDICATORS OF CHANGE ACROSS LAND USE AND SOIL DIVERSITY

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DEDICATION

I dedicate this thesis to my parents, for their unwavering support and faith in me.

ABSTRACT

Soil is an important natural resource and has the potential to provide food security, mitigate climate change, and protect coastal and inland ecosystems from degradation if it is in, or is restored to, a healthy and resilient state. Measuring soil health allows land managers to track improvements or degradation over time and optimize their management strategies for long term benefits of the land by use of a soil health index. However, such soil testing methods and analysis necessary to monitor changes are not currently established for the unique soils of Hawai‘i. Ten soil series samples within six soil orders were collected from 22 field sites on Oahu, Molokai, and Maui, spanning a range of soil conditions and land cover including cropland, forest, and grassland to capture high diversity. A suite of 30 potential soil health parameters measured physical, chemical, and biological soil properties. Multivariate analysis identified those parameters which could be used as indicators of soil health based on their sensitivity to changes in the soil characteristics as well as their practicality for routine soil testing. Current and previous management based on land use history showed the greatest association to the variance in soil data and created an associated potential gradient of soil health. Nine indicators from a reduction process using quantitative and qualitative criteria comprise the recommended soil health indicators for detecting differences in management practices across a spectrum of soil health and include: water holding capacity, water-stable mega-aggregates, percent total organic carbon, C:N ratio, 24 hour CO_2 burst, β-glucosidase, β-glucosiminidase, hot water extractable organic carbon, and potentially mineralizable nitrogen. The proposed indicators were effective in detecting differences in management across the full landscape as well as qualitative differences in soil management within soil order, which highlighted soil taxonomy as an important inherent

contributor to data variance. These most practical and sensitive indicators of soil health will be used in further field trials which will be necessary to determine the effectiveness of implementing new soil health management strategies as well as to identify the quantitative thresholds used in developing scores in a Hawai‘i soil health index.

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CHAPTER 1. INTRODUCTION TO SOIL HEALTH*

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1.1 Earth's precious resource, soil

Defining soil

The origins of soil science began in the early 1800's with the most significant transitions in the field happening in more recent decades, and definitions of 'soil' have varied over the centuries. A Google search defines 'soil' as "the upper layer of earth in which plants grow, a black or dark brown material typically consisting of a mixture of organic remains, clay, and rock particles," where the soil is portrayed in a rather simple and non-complex manner (OED, Web). In contrast, those who study soils define it more specifically to be "a dynamic natural body composed of mineral and organic solids, gases, liquids, and living organisms which can serve as a medium for plant growth and that has properties resulting from the integrated effects of climate and living organisms acting upon parent material, as conditioned by topography, over periods of time" (Brady and Weil, 2008). With this more explicit definition, we see the soil's importance connecting Earth systems involving plants, organisms and the atmosphere.

Soil organic matter

The composition of most undisturbed soil consists of approximately 25% air (as pore space), 25% water, 45% mineral particles, and 5% as organic matter. When soil is compacted, the mineral ratio is increased as the pore space, water, and organic matter portions all typically decrease. Soil organic matter (SOM) includes plant, animal, and organism residues/tissues at various stages of decomposition as well as microbial-synthesized substances (Brady and Weil, 2008). While organic matter represents a very small portion of a soil, it plays a fundamental role influencing all aspects of soil function. Organic matter in the soil is largely made up of carbon, which provides a substrate as well as a food source for soil life and is actively cycled throughout all natural systems. With its main constituent carbon, SOM contributes to a soil's fertility, atmospheric carbon sequestration, and ecosystem productivity (Harden et al., 2017).

Soil functions

Six key roles of soil have been identified for any ecosystem which are 1) a medium for plant growth, 2) a system for water supply and purification, 3) a recycling system for nutrients and organic wastes, 4) a habitat for soil organisms, 5) a modifier of the atmosphere, and 6) an engineering medium (Brady and Weil, 2008). Soil assists in many important ecosystem services, which are the benefits humans obtain from natural systems, such as provision of clean water and climate regulation (Brady and Weil, 2008). Understanding soil processes goes beyond the laboratory to encompass a larger holistic system, as it impacts and is impacted by many components of an environment such as vegetation, animal inhabitants, precipitation, pollution, agriculture, climate, and human activity.

1.2 Historical moments in soil management

Agriculture evolution

Soil has been cultivated to support agriculture long before the scientific understanding of it arrived. With the increasing global need for food production and environmental sustainability, the need to further understand soil health continues to grow. Standard practices of modern agriculture, such as tillage and fertilizer application, lead to the loss of SOM and hence considerable degradation of soil quality and function. Within the last century in the United States and particularly in Hawaiʻi, agricultural land has experienced excessive tilling and poor management. A clear historical example of such poor soil management was the Dust Bowl Era. While it was the inevitable drought from 1931 to 1939 that ultimately led to the Dust Bowl, the soil quality was worsened due to excessive tillage of the land prior to this climatic condition (Baumhardt, 2003). This landmark event has pushed agriculture to develop practices better suited to the needs of specific soil types and natural conditions of the land, rather than attempting to impose farming practices suitable for humid regions on the semiarid Great Plains, as was seen during the Dust Bowl (Baumhardt, 2003). The conventional practices of tillage and fertilizer use pose the risk of soil organic matter loss by multiple mechanisms, such as increased carbon oxidation and damage to the microbial activity (Al-Kaisi and Yin, 2005). These same trends in agriculture are responsible for the degraded state of soil found across the state of Hawaiʻi, due to plantation agriculture and commercial farming using conventional soil management practices.

Historic events such as the Dust Bowl along with many advances in technology have contributed to the growth of the soil health topic. Norman Borlaug's 'Green Revolution' also played a crucial role as it allowed farmers to view soil as a system that can be manipulated with alterations in soil chemistry and composition using improved methods of soil research and technology (Tilman, 1998). The Green Revolution was in part dependent on the creation of the Haber-Bosch process, or industrial nitrogen fixation, which assisted to manipulate soils for the growth of agriculture worldwide (Erisman et al., 2008). With the ability to fix atmospheric nitrogen into a plant available nitrogen fertilizer, typically a limiting essential nutrient in many soil systems, the production of food was able to expand and intensify with much less restriction and became more available globally (Brady and Weil, 2008). However, with this great power to create endless amounts of nitrogen fertilizer came great responsibility to be mindful of the impacts of expanding agriculture on the soil and surrounding ecosystems. For example, the readily-available forms of nitrogen from the Haber-Bosch process has led to serious issues in water quality and eutrophication, a negative impact of nutrient surplus on water ecosystems. By altering the ratios of soil nutrients, chemistry, and composition during the Green Revolution, yet still seeing degradation in soils, it became apparent that there was more to understanding soil management than the inherent soil characteristics such as nutrient cations, soil texture, or drainage class. As a result, agricultural science began to acknowledge how soil functioned as a larger dynamic system requiring a larger scope of focus and attention.

Emergence of the soil quality concept

The term 'soil quality' is a relatively new concept that evolved throughout the late 1900s after the merging topic of 'sustainable agriculture' gained momentum in response to the need for increased global emphasis of soil management (Karlen et al., 2008). One of its early definitions in 1989 was "the ability of a soil to support crop growth which includes factors such as degree of tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH changes, nutrient capacity, and so forth." It went on to be described in 1992 as "the capability of soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment" (Doran and SSSA, 1994). As the term evolved to be more mindful of the whole ecosystem with humans included, a broader encompassing term, 'soil health,' developed which is commonly defined as "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain or enhance the quality of air and water, and promote plant, animal and human health" (Doran et al., 1996, Doran and Zeiss, 2000, Laishram et al., 2012). A difference in this evolution of terms is the perception that ‘soil health’ tends to include more biotic components of soil and expands the goals of soil maintenance beyond those which serve only the purpose of agricultural needs (Anderson, 2003, Laishram et al., 2012).

The evolution of the ‘soil quality’ concept to include the term ‘soil health’ supported the advancement of soil as an ecosystem science and literature on soil health could expand the boundaries of traditional soil science. With data available until 2008, the comparison between the frequencies of printed phrases ‘soil quality’ and ‘soil health’ since 1900 shows that a notable presence of ‘soil health’ in printed literature began in the mid-1990s in union with a steady increase in the use of ‘soil quality’ (Figure 1.1). Around the year 2000, the term ‘soil health’ continues to slowly increase and ‘soil quality’ simultaneously appears to take a sharp decline in frequency of use in published works. However, as a more widely accepted term, ‘soil quality’ still shows up more frequently than ‘soil health’ in 2008.

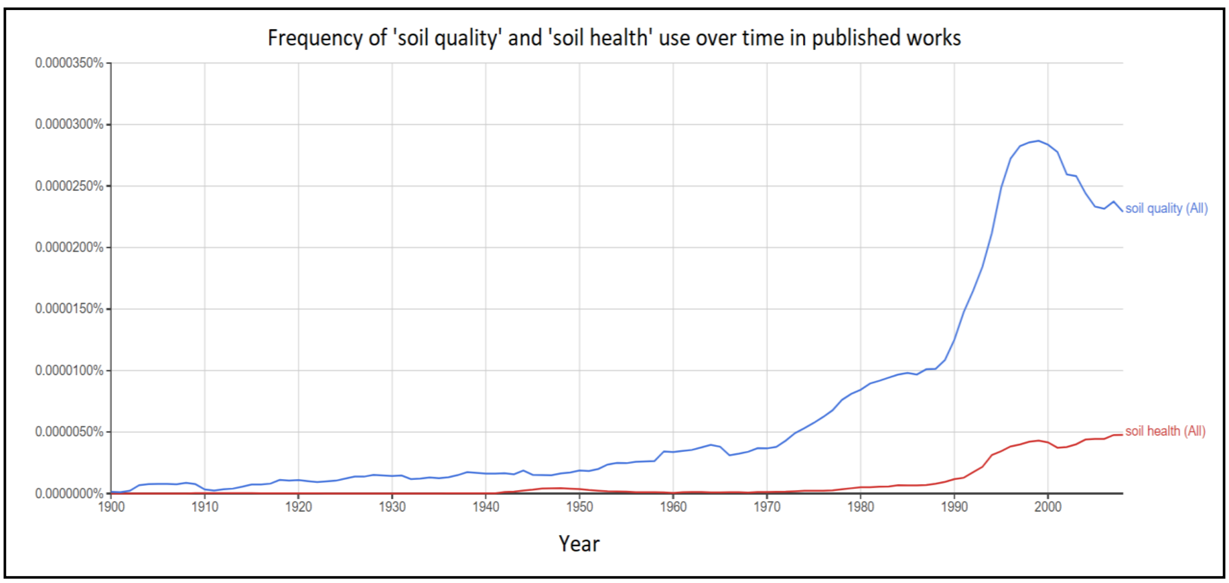


Figure 1.1 The relative frequencies of terms ‘soil quality’ and ‘soil health’ over time, demonstrating the decline in use of ‘soil quality by 2000 after continual increase since 1900, and the steady incline of ‘soil health’ beginning in the mid-1990’s (Google Ngram tool, https://books.google.com/ngrams).

While these terms are often still used interchangeably and with various definitions, the term of interest for modern soil assessment, 'soil health,' can be referred to as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans" (NRCS, 2017). This holistic focus on 'soil health', in place of 'soil quality', encourages opportunities to understand and manage whole soil ecosystems as well as introducing challenges as to how to quantify such a vast area of science with expansive global diversity and importance.

1.3 Impact of soil on climate change and environmental sustainability

Global warming and the reduction of soil carbon stocks

Historical moments are not only important for reminding modern farmers of the potential consequences of poor soil management, they also coincide with long-term damage of such consequences to the global climate. Human activities, such as deforestation, have led to increases in atmospheric carbon dioxide (CO_2, a greenhouse gas), posing serious threats to the globe via the greenhouse effect, such as sea level rise, rising temperatures, and more frequent and intense natural disasters. In a natural ecosystem, soil has the ability to store carbon long-term (referred to as carbon sequestration) that would otherwise be emitted from the soil or remain in the atmosphere. Poor agricultural practices disrupt the function of natural soils, which typically act as a sink for carbon. Other large natural sinks for carbon are in forests, atmosphere, and oceans, however, soil is estimated to contain more carbon than in all plant life and the atmosphere combined and is Earth's largest biogeochemically active terrestrial pool of carbon (Jackson et al., 2017).

Replenishing soil carbon stocks through carbon sequestration is a potential solution to mitigate climate change, but it requires more research to understand the physical, chemical, and biological processes involved that increase soil carbon storage. In doing so, research must also continue to examine how soil carbon can be protected from decomposition to avoid releasing it back into the atmosphere through microbial metabolism. Soil health relies heavily on both the presence of organic matter and life in the soil, which correlate to and are reliant on the soil organic carbon content. Promoting the accumulation of organic matter, and hence, organic carbon, and supporting microbial decomposition in the soil are necessary processes to be included in soil health management plans. Thus, supporting soil health through proper management is not only vital to continue agriculture, but it also connects soil health to climate change mitigation and building soil carbon stocks.

Soil as a facilitator of agroecosystem health

Such global changes and population growth suggest that our dependence on soil as a vital resource will continue to increase, along with our understanding of the complex interactions and functions it has with the environment (Karlen et al., 2003). In addition to climate control, soil in good health may impact pest population reduction, support biodiversity, increase soil fertility, improve disease resistance, reduce the cost of agricultural practices, and increase drainage of water systems, to name just a few (Janvier et al., 2007, Brady and Weil, 2008). Soil in poor health can lead to issues related to but not limited to: erosion, nutrient depletion, slow water infiltration, soil contaminant accumulation, soil compaction, low biodiversity, and plant disease (Soil Health Institute, 2017). The outcomes of improving soil health can also be seen at global scales with examples such as extreme weather resilience and improved air and water quality (Soil Health Institute, 2017).

Similar to human health, where symptoms of poor health and disease can be complex and difficult to fix with one perfect cure, challenges with soil health are complex and tied to their environments and thus, are treated differently based on climatic zone, intended function, culture, and resources available. To precisely improve soil conditions, like improving global human health, common language, measurements, and communication are crucial to allow for information to be shared and advances to be made. The success of better assessing soil health in Hawai‘i could lead to improvements in food security, water purification and conservation, wildlife conservation, climate change mitigation, and relief from financial challenges of agriculture (Brady and Weil, 2008).

1.4 Assessments of soil health

Inherent soil qualities and soil taxonomy

Over time, soil health studies have been transformed from encompassing mostly inherent qualities of soil into more dynamic qualities that identify soil as part of a complex ecosystem capable of either restoring or degrading the surrounding environment and its ecosystem services. With soil health now commonly viewed in a dynamic way, current research explores ways to better define the spectrum of soil health. One approach of soil studies is to simplify soil into two groups of characteristics: inherent and dynamic qualities. The inherent soil qualities focus on characteristics that on a large scale are not easy to change, and can be defined as “the aspects of soil quality relating to a soil’s natural composition and properties influenced by the factors and processes of soil formation, in the absence of human impacts" (NRCS, 2018). The inherent soil properties closely align with the original perspective of 'soil quality,' as they pertain mostly to aspects of the soil that are easily measured and important for soil taxonomy such as texture, pH, bulk density, and organic matter content to differentiate between soil types, and mostly in the absence of human impacts (Karlen et al., 2003a).

Each of the world's soils belongs to one of the 12 taxonomic orders described by the U.S. Soil Taxonomy, based mostly on the inherent soil properties (Brady and Weil, 2008). Due to the diversity in these characteristic combinations, over 20,000 varieties, or series, of soil have been characterized in the United States alone. For example, the 'Mollisol' soil order is characterized by rich fertile soils with high organic matter content in the surface horizon developed from grasslands, with high cation exchange capacity (CEC) and high base saturation (Brady and Weil, 2008). A lengthier taxonomic name, 'very-fine, smectitic, calcareous, isohyperthermic cumulic vertic endoaquaolls,' describes a specific Mollisol soil variety unique to its taxonomic conditions. Of the 12 soil orders, 10 are found in the Hawaiian Islands, including hundreds of different soil varieties within those soil orders. The amount of soil diversity in Hawai'i alone introduces many challenges, as well as opportunities, when attempting to apply global soil health concepts to all soils. The inherent qualities of soils differentiate them across taxonomy and result in a diversity of their measurable values related to soil health. Therefore, it is impractical to directly compare values reliant upon soil inherent qualities between varying taxonomic groups without standardization for such differences.

Dynamic soil qualities

In contrast to the inherent soil properties of a soil, the dynamic soil qualities can be changed with soil management, land use, and climate change. Similar to the connection between inherent qualities and 'soil quality,' identifying the dynamic qualities of soils has emerged in unison with the term 'soil health,' as it builds off of the inherent soil properties and also provides more detail of the surrounding ecosystem, such as management-dependent soil changes like soil bulk density. Dynamic properties can be defined as "the soil properties that change as a result of soil use and management over the human time scale" (NRCS, 2018). This scope of soil properties associated with the soil health concept typically focuses on the top 0 to 15-30 cm of the soil profile and considers the status or condition of the soil due to land cover or management decisions (Karlen et al., 2003a). Examples of impacts from management that are important to consider when assessing soil health are: soil compaction by machinery, tillage of the soil, biodiversity present, crop type, irrigation, and fertilizer use (Brady and Weil, 2008). The complexities of unique soil taxonomy and dynamic impacts combined demonstrate why there is a need for soil assessments that capture many soil properties and functions and why one index may not be adequate to serve all soils.

Indicators of soil health

Soil health indicators are categorized into measurable attributes used to evaluate a soil's overall health or detect changes in health. Indicators are quantifiable values relative to an optimal level or 'natural soil state' and are applied across environmental, biological, economic, social, institutional, and political disciplines to better grasp soil conditions and track soil health changes (Allen et al., 2011, Dalal et al., 2003). These indicators serve to assess soil health by linking functional relationships of various soil characteristics and identifying these changes with correlations to land management and environmental impacts (Allen et al., 2011, Dalal et al., 2003, Doran, 2002, Doran and Zeiss, 2000). Five critical soil functions have been identified for healthy soil in Hawaiʻi based off the essential functions of a soil in the greater global ecosystem as well as the local ecosystem, and which also support current goals of the state legislature to aggrade this natural resource (Table 1.1).

Table 1.1 The five identified desired critical soil functions for healthy soil in Hawaiʻi and their related measurements. Critical soil functions are determined by assessing the spectrum of Hawaiian land uses in regards to fulfilling the current and future needs of the land.

CRITICAL SOIL FUNCTION	RELATED MEASUREMENTS
Nutrient cycling	Enzymes, microbes, nutrient content, pH
Carbon storage and cycling	Carbon content, carbon pools, aggregates, microbes, crystalline Fe/Al content
Water infiltration and supply	Water holding capacity, compaction, bulk density, aggregates, soil hardness, texture
Soil life and biodiversity	Microbial diversity, microbial activity, available substrate, enzymes
Medium for plant growth	Bulk density, nutrients, water relations, aggregates, soil hardness, pH

The major indicators of soil health can be separated into three categories: chemical, physical, and biological. Within each category is a subset of indicators used to represent a critical function of soil within the assessment of a soil's overall health (an example of those identified for a Northeast region in the United States are presented in Table 1.2). For example, indicators such as available bulk density, soil hardness, and aggregate stability are considered physical; mineralizable nitrogen and microbial respiration, are considered to be biological; and pH, macronutrients, and total carbon, are considered chemical (Karlen et al., 2003, Moebius-Clune et al., 2016). The scientific relevance of a suitable indicator is considered based on things such as its sensitivity to management, good correlation to beneficial soil functions, cost and ease to measure, and accuracy in measurement (Moebius-Clune et al., 2016, Laishram et al., 2012).

To select potential indicators for a soil health test, a variety of approaches are available and no one correct way exists. Karlen et al. (2001) suggest two common approaches to acquire a minimum data set (MDS) including using expert opinion as well as principal component analysis (PCA), while acknowledging there are limits to the available information and local adjustments are typically necessary (2001). The PCA approach relies on a statistical technique to identify the indicators that best describe the greatest variation within data, and which are then considered to be more sensitive (Karlen et al., 2001, Andrews et al., 2002). In contrast, using expert opinion may call upon multiple scientists to represent the interdisciplinary backgrounds of soil health to determine important soil functions and practical indicators based on goals of the group (Karlen et al., 2001). Those seeking to assess soil health may choose a single or combined approach to identifying a MDS, as the objective for index development should be to develop an assessment made to a scale and sensitivity that suits the questions being asked and practical considerations for indicator selection will widely vary (Karlen et al., 2001).

The Cornell Soil Health Assessment recommends choosing indicators for an index score based on the evaluation of a soil's sensitivity to change in management practices, relevance to the soil processes and functions, consistency and reproducibility, ease and cost of sampling, and the cost of analysis (Moebius-Clune et al., 2016, Laishram et al., 2012). In reference to these parameters, the Cornell Soil Health Assessment has narrowed down from many options, just nine indicators to use for a soil health index (Table 1.2). They include: surface and subsurface hardness, water stable aggregates, available water capacity, active carbon, organic matter content, soil protein, soil respiration, and soil chemical composition (Moebius-Clune et al., 2016). Some of these have test methods established that have remained useful and relevant, such as nutrient levels (chemical composition), while the methods of some, such as water stable aggregates, are under debate as techniques are still being improved upon based on soil type differences and access to improved technology (Silva et al., 2015, Tisdall and Oades, 1982). Since not all indicators are best for all soils and a MDS is more practical than an elaborate and complex set, it is important to create indices that are easy to measure and interpret and are also robust.

Table 1.2 A list of 43 potential soil health indicators developed by the Cornell Soil Health Team for use towards a soil health assessment protocol (Moebius-Clune et al., 2016).

Physical	Biological	Chemical
Texture	Root pathogen pressure assessment	Phosphorus
Bulk density	Beneficial nematode population	Nitrate nitrogen
Macro-porosity	Parasitic nematode population	Potassium
Meso-porosity	Potentially mineralizable nitrogen	pH
Micro-porosity	Cellulose decomposition rate	Magnesium
Available water capacity	Particulate organic matter	Calcium
Residual porosity	Active carbon	Iron
Penetration resistance at 10 kPa	Weed seed bank	Aluminum
Saturated hydraulic conductivity	Microbial respiration rate	Manganese
Dry aggregate size (<0.25 mm)	Soil proteins	Zinc
Dry aggregate size (0.25 - 2 mm)	Organic matter content	Copper
Dry aggregate size (2 - 8 mm)		Exchangeable acidity
Wet aggregate stability (0.25 - 2 mm)		Salinity
Wet aggregate stability (2 - 8 mm)		Sodicity
Surface hardness with penetrometer		Heavy metals
Subsurface hardness with penetrometer		
Field infiltrability		

Ultimately, the relevance of the selected indicators depends on the soil type and climate and what soil function is intended to be attained or maintained (Brady and Weil, 2008). A few specific factors to be considered as impacting indicator selection may include vegetation, topography, temporal variation, landscape position, tillage effect, soil water changes via irrigation or rainfall, temperature regimes, and anthropogenic decisions (Karlen et al., 2001). While it's tempting to use a robust index with dozens of indicators, this is often impractical and previous studies have shown that careful selection of fewer soil health indicators can effectively be used to judge the impacts of management impacts on soil sustainability (Lima et al., 2013, Andrews et al., 2002a, Kelting et al., 1999). To achieve a robust and reliable measure of soil health, it is crucial to select indicators that are stable and do not vary widely on a short-term basis.

While chemical and physical indicators are typically straightforward to measure, the nature of biological indicators as a function of living organisms and the roles they play in soil health are often more complex and therefore difficult to isolate (Moebius-Clune et al., 2016). Despite this challenge, soil biology is foundational to many important soil functions. For example, six key roles of soil microbes are: decomposition of organic matter (crop residue), mineralization and recycling of nutrients, fixation of nitrogen, detoxification of pollutants, maintenance of soil structure, biological suppression of plant pests, and reduction of parasitism and damage to plants (Stirling, 2014, Brackin et al., 2017). These functions are also closely linked with both the chemical and physical properties of soil as they are dependent upon and contribute to the fluxes and flows of carbon, nutrients, changes in soil pH, soil structure, and aggregate stability, to name a few. In addition, microorganisms respond rapidly to environmental stress, allowing them to be a powerful tool in soil health assessment by indicating early signs of change in soil health, at times preceding detectable change in physical or chemical indicators (Nielsen et al., 2002). Because of their diverse and complex interactions with soil and the more recent addition of biological indicators into the realm of soil health as a leading dynamic component, they are an area with large gaps of knowledge and possess great potential opportunity for growth in developing soil health indices (Kibblewhite et al., 2007, Karlen et al., 2003a).

Indicator selection for Hawai'i

To begin tailoring a Hawai'i soil health index, a wide range of indicators have been selected based on consideration of those widely accepted from existing soil health tests of other regions, and by calling upon local expert knowledge of Hawaiian soil (Table 1.3) (Karlen et al., 2001). A set of 20 potential indicators of soil health were compiled from expert opinion and resources available online from the Cornell Soil Health Assessment, Haney Soil Health Index, and USDA-NRCS. Indicators related to soil organic carbon stabilization were included because carbon plays a central role in soil health, and connects global carbon cycles to soil organic matter and soil life. While 20 indicators are impractical for a routine soil health index, the list represents a logical starting point to create a reduced list of indicators for Hawaiian soil health.

Table 1.3 Soil indicators selected for developing a soil health index in Hawai‘i based on interest in improving desired soil functions for nutrient cycling, carbon storage, water infiltration and supply, biodiversity of soil life, and providing a productive medium for plant growth.

	INDICATOR	FUNCTION	METHODOLOGY
PHYSICAL	Aggregate stability	Infiltration, porosity, resistance to erosion, C storage	Wet-sieving, macro and mega water-stable aggregates
	Bulk density	Porosity, rooting environment, tilth	Soil core
	Water holding capacity	Plant water relations	Capillary action
	Texture	Infiltration rates, microbial distribution and soil fertility	Particle size analysis for percent sand, silt, and clay
	Soil hardness	Soil friability, drainage, tilth	Penetrometer used at surface and 15cm depth
CHEMICAL	Total organic carbon and nitrogen	Natural resource reserve and microbial activity	Combustion with Elemental Analyzer
	Extractable nutrients (Ca, Na, P, K)	Metabolic rates, nutrient uptake, and nutrient availability	Mehlich III extraction
	pH	Metabolic rates, nutrient uptake, and nutrient availability	pH meter
	Poorly and non-crystalline minerals	Organic matter accumulation, water relations, soil aggregation	Al + 0.5Fe, from non-crystalline bound Al/Fe extraction and quantification with ICP
	Crystalline Fe oxides	Organic matter accumulation, water relations, soil aggregation	Crystalline-bound Fe extraction and quantification with ICP, minus organic and non-crystalline bound Fe values
	Hot water extractable N	Nitrogen availability and nutrient uptake	Hot water extraction and analysis for dissolved inorganic nitrogen
	Total dissolved N and C	Energically available, plant available, mobile	Water extraction and analysis for total nitrogen and organic carbon
BIOLOGICAL	Hot water extractable C	Energy source for microbes, microbial biomass	Hot water extraction and analysis for dissolved organic carbon
	Carbon mineralization	Readily available microbial substrate	4 month soil incubation
	Soil respiration	Metabolic activity of the soil microbial community	24 hour CO2-C burst
	Microbial community	Microbial community structure	PLFA
	Enzyme extractions	Microbial activity, decomposition of substrates and nutrient cycling	Beta-glucosidase, Beta-glucosiminidase, Acid phosphatase
	Potentially mineralizable nitrogen	Soil biological activity and available substrate for N mineralization	Nitrate and ammonium release during 7-day anaerobic incubation
	Microbial functional diversity	Diversity/richness of microbial population	Amplicon sequencing
	Arthropods for richness/diversity	Diversity/richness of invertebrate population	Berlese funnel

Building soil health indices

The common approach to creating most soil health indices involves combining soil health indicators into varying scoring systems which are then integrated into creating one index (Karlen et. al., 2008). General guidelines of index development are stated by Karlen et al. to include the following steps: 1) identifying critical soil functions, 2) selecting meaningful indicators for those functions, 3) developing appropriate scoring functions to interpret the indicators for various soil resources and finally, 4) combining the information into values that can be tracked over time to determine if the soil resources are being sustained, degraded, or aggraded (2001). Once indicators are reduced from a potential list (Table 1.3) using those methods suggested (PCA and expert opinion), many formulas and options exist for weighting the value of indicators to sum into the final score. However, in general, the indicators are scored considering their value as 'more is better' such as organic matter, deviation from 'optimum' such as pH, or 'less is better,' such as bulk density (Karlen et al., 1994, Moebius-Clune et al., 2016). Ranges of indicator values are typically assigned an integer value (e.g., 0-10) or nonlinear scoring function, as appropriate for the selected indicators. With these unitless scores, they can be combined across all index indicators to obtain a final health "score." There are, however, a few hurdles with this approach of assigning how heavily to factor in different indicators or threshold values, such as determining which indicators remain relevant over time, the inherent differences of the soil types being compared on the same index, and the specific goals for land use (Gugino, 2007). Using the strength of the PCA correlations can also provide insight on how to weigh various indicators (Andrews et al., 2002).

The soil management assessment framework (SMAF) developed by Andrews et al., (2004) and further developed by Wienhold et al., (2009) provides an additional method for a scoring curve protocol of soil health indicators. SMAF uses non-linear scores to develop unitless scores from algorithms or logic functions following the form of more is better, less is better, or optimal values (Weinhold et al., 2009). From a selection of potential indicators, values from a large dataset are plotted with a range of environmental values and relationships are described with curve-fitting software. The algorithm-fit scoring program is then validated with a different set of data from that used to develop the algorithms. Limitations to the application of this process include that climate and inherent properties can impact results between sites, and that full datasets of values need to include a measure of soil function, similar to having a set response variable (Weinhold et al., 2009).

Another consideration for soil health assessment is again the human factor of assessment, which emphasizes the value of an experienced soil scientist to evaluate soils. When available, expert opinion can be utilized to not only assist in selecting indicators for a MDS but also in determining optimal values (Lima et al., 2013). While this component of assessment is often thorough and effective, it is also limited by the time and proximity of those experienced in soil health and can be subjective. Continued studies in on-farm assessment and validation are necessary to further develop functional soil health assessment indices by region and expand such a valuable knowledge base (Kinyangi, 2007, Allen et al., 2011).

Challenges observed in Hawai‘i

Agricultural land in Hawai‘i has been dominated by intensive monoculture farming for more than a century, leaving degraded soils with negative impacts such as loss of organic matter, decreased nutrient cycling and supply capacity, decreased water infiltration, susceptibility to erosion, acidification, and accompanying toxicity. In addition to these conditions, Hawai‘i’s unique topography, tropical climate and precipitation gradients have led to a variety of soil types and require a soil health index with adequate flexibility to address such diverse agroecosystems. Current soil health indices have not yet been tailored for Hawaiian soils and there is a lack of research related to indicator testing for Hawai‘i soils. While not directly applicable to Hawai‘i, existing tests such as the Cornell Soil Health Assessment and Haney Soil Health Index do provide useful index structure to assist in the development of a Hawai‘i soil health index (Table 1.3). However, in order to develop a Hawai‘i-specific soil health index, research on the sensitivities and threshold values of indicators under local conditions is required (Lima et al., 2013). In addition, selecting indicators for a Hawai‘i soil health index that are best understood and hold the most meaning for Hawaiian farmers is likely the best way to link soil science with farmer decision-making (Roming et al., 2005).

1.5 Using soil health tests

Cost and analysis

To measure soil health, many options currently exist that use a range of indicators and methods, which vary in costs, reliability, comprehension, and real-life applicability. A basic soil health test offered by Cornell University is $60, but can easily reach $200 depending on the depth of personalized result interpretation, equipment needed, and add-on indicators measured, which is a common price range for current soil health testing facilities in the United States. Analysis time can range from a few days for simple in-field tests, to over a month for those requiring greater laboratory examination. The Cornell Soil Health Assessment and the Haney

Soil Health Index are two current approaches for soil health assessments in the United States. The test results provide a farmer with a soil health ‘score’ derived from a soil health index, demonstrating how it stacks up in comparison to qualities of soils with known health and possessing similar functions and qualities, or to the same soil from a previous sampling. The score can then be broken down within the physical, chemical, or biological categories and used to assess soil health improvement or degradation in each category. These tests also may offer management suggestions based on the type of results package a client requests. With the recommended guidance, the land manager can choose to add organic matter, use more or less fertilizer, select appropriate types of fertilizers, adjust soil disturbance, irrigation, or crop type, for example. Over time and with the use of continued testing, management styles can be tracked to show their effects upon the soil’s health and be used as a tool to measure changes in the soil as a result of management, land use, or environmental changes the land undergoes.

Soil health improvement strategies

After a soil health test assesses or scores the condition of the soil, the recommended options for improving the soil health constraints may be considered (Moebius-Clune et al., 2016). Alternative soil management practices should be implemented gradually and with careful monitoring to adjust to the characteristics of the land and ideally with the assistance of a soil specialist (Moebius-Clune et al., 2016). Noticing issues with soil in the early stages of transitioning the land with new soil health goals can help to keep the approaches relevant to the soil problems and to avoid expensive crop failures. Four common strategies used to improve soil health are: reducing tillage intensity, crop rotations, cover cropping or inter-seeding, and adding inoculants or amendments such as organic matter (Moebius-Clune et al., 2016). While there are endless combinations of options and outcomes when using these concepts, incorporation of these techniques can reduce the disturbance to the soil biotic communities, increase species diversity and disease resistance, improve nutrient cycling, boost the soil organic matter, and improve soil structure.

Optimizing soil carbon sequestration to improve soil health and climate change mitigation

By carefully tracking soil health test changes along with specific farm practices, soil researchers could draw more accurate correlations between soil health and carbon sequestration potential. Sequestration varies across soil types and regional variables regarding SOM content and carbon storage which contribute to climate change mitigation. As a result, farmers could tailor their soil management practices to optimize soil health as well as climate change mitigation by building SOM. Soil health improvement and soil carbon sequestration may be optimized by similar processes, however these have not been clearly identified for the soils unique to Hawai‘i. Soil practices in other regions shown to support soil carbon sequestration are 1) working the soil less, for example with no-till methods 2) keeping the soil covered with vegetation rather than bare 3) planting intermediate crops, row intercrops, and grass strips 4) creating field hedges 5) optimizing pasture management such as longer grazing periods and 6) restoring degraded soils (Minasny et al., 2017). Additionally, soil types are known to have varying potentials to sequester soil carbon, with certain tropical soils existing on the higher end of soil carbon sequestration potential (Jackson et al., 2017). Based on the soil types and practices we know to impact both soil health and soil carbon sequestration potential, it is expected that conducting soil health testing across Hawai‘i’s various land management could guide the restoration of soil health and contribute to climate change mitigation.

1.6 Social perspectives of soil health

Relevance of soil health to farmers

A soil health test can improve the outcome of agricultural efforts and benefit the surrounding environment, however, it is unknown if such a tool is being utilized in Hawaiʻi or how it is used by farmers to impact management decisions. Soil health testing assesses the quality of a soil ecosystem in relation to various land use goals. Ideally, growers can turn to these assessments so that they have effective overall planning for their soil, can identify constraints, monitor change, and measure progress (Moebius-Clune et al., 2016). Since the methods of measuring soil fertility are well developed in respect to crop production outcomes, fertility/nutrient tests are currently more widely adopted than a soil health test. However, while quite useful when used correctly, only a quarter of American farmers are testing for soil fertility/nutrients, and for those that are, they typically lack the necessary resources to interpret their soil tests and apply the information to their management practices (Lobry de Bruyn and Andrews, 2016).

Soil health improvement is a slow process and accurately recording change in relevant indicators is crucial to see the impact of management practices over time. Since these changes in soil health happen at the human time scale, particularly in degraded soils, it is ideal that soil tests be used regularly as a 'decision aid' for long term soil health planning (Lobry de Bruyn and Andrews, 2016). A farmer using a Hawaiʻi soil health index can actively assess the effectiveness of management practices (Figure 1.2). Used regularly, a location-specific soil health test should accurately give a farmer answers to questions such as "did the implemented farming practice improve, maintain, or degrade the condition of the soil?" The recommendations for restoring soil health are especially important for many developing regions that have become degraded. In some areas that are particularly isolated with limited resources for agriculture, soil health improvement strategies such as adding organic matter and rotating crops are realistic options to ‘kick-start’ low-fertility or degraded systems (Kibblewhite et al., 2007).

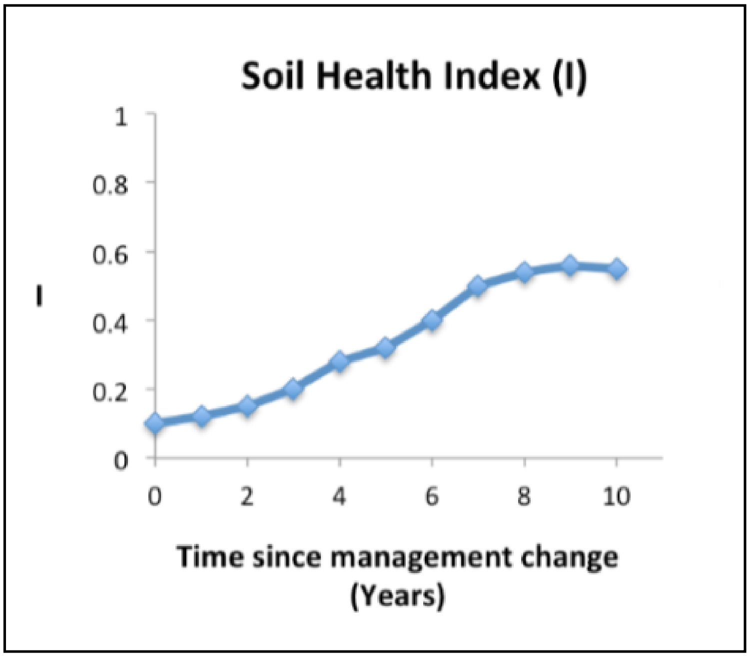


Figure 1.2 An example of how results from a developed Hawai‘i soil health index can be used by a farmer over time to track soil health after a management change, where the range of values are 0-1 with one being the healthiest. Scores for the index are generated from measured physical, chemical, and biological soil parameters.

Understanding farmer perceptions

In Hawai‘i, it is unknown how soil health or fertility testing is being utilized among farmers. Due to lack of available data, the reasons why some farmers may not be using soil testing such as cost, analysis time, or uncertainty in the applicability to their management are unrecognized. For this reason, there is a gap of knowledge as to how to best provide soil testing resources and boost farmer engagement. Further research should attempt to identify user participation as well as applications of soil test information to better support farmer goals as well as expand available soil data in the state.

Successful efforts in evaluating human thought processes regarding belief systems and related behaviors holds the key to unlocking existing barriers of communication between farmers and researchers, extension workers, and policy makers. Regarding the Theory of Planned Behavior postulated by Ajzen (1991), farmers may have the intention to sustain soil health on their land, but the lack of appropriate resources can introduce behavioral controls and alter the intended behavior of a farmer, such as diminished efforts to utilize soil health building practices due to poor soil monitoring resources (Bhattacherjee, 2012). After addressing issues that impact farmer interest in long-term land management plans such as land ownership and lease length, understanding the perception of soil health testing by a farmer is arguably one of the most crucial aspects to consider when attempting to implement a new soil health index with the goal of improving long-term health of soils and conservation planning for land managers. The process of cognitive mapping, involving a series of questions to assign quantitative values to an individual's perceptions, is one effective way of evaluating the gaps of communication between the scientific community and real-world application. Integration of the farmer perspectives and empirical knowledge can be particularly useful in low-input systems where resources are mostly derived locally (Mairura et al., 2007). With the creation of a mental map from on-farm participatory research, Hawaiʻi-specific soil knowledge could effectively assist in developing the most applicable and appropriate soil and crop management systems (Mairura et al., 2007).

Big picture pertinence of soil carbon

In addition to improving soil directly for agriculture benefits, the ability to assess the health of a soil also facilitates land valuation and pricing of soil economically and gives soil health initiatives more momentum from a political standpoint (Moebius-Clune et al., 2016). Effective responses to the degradation of soils must emanate from policy change that pertain to soil management by land managers (Lobry de Bruyn and Andrews, 2016). Accurate testing with reproducible methods for soil health assessment is also of importance in ‘carbon farming,’ where a soil is managed for its ability to sequester carbon from the atmosphere as a strategy for climate change mitigation (Lal, 2004). Land being regulated for carbon farming can be considered in regions that support a carbon tax system, where carbon emissions can be offset by the carbon farming potential of certain soils in a carbon economy. The Hawai‘i State Legislature has signed into law Act 33 in 2017, which established a Greenhouse Gas Sequestration Task Force whose mission is to improve soil health and promote carbon sequestration in Hawai‘i’s agricultural, aquacultural, and agroforestry sectors (Office of Planning HI, 2018). Locally, this represents a critical step in Hawai‘i’s efforts to adopt the goals of the Paris Climate Agreement and become a national role model. Additionally, it supports Hawai‘i’s statewide commitment for clean energy, natural resource management, local food, smart sustainable communities, solid waste, and green education and workforce by 2030 (Office of Planning HI, 2018). Globally, initiatives such as ‘4 per 1000 Soils for Food Security and Climate’ seek to increase soil carbon stocks by 0.4% per year to halt annual increases in atmospheric CO_2 which contributes to global climate change (Minasny et al., 2017). Soil science applications such as these examples are gaining momentum worldwide, opening more avenues of opportunity and funding in applied science for real-world solutions.

CHAPTER 2. REFINING POTENTIAL SOIL HEALTH INDICATORS FOR HAWAI'I'S DIVERSE SOILS

2.1 INTRODUCTION

More than a century of intensive agriculture has left much of the formerly productive Hawaiian soil in a degraded state, which currently exists as a diverse landscape of various land use and management. Soil is an important natural resource and has the potential to provide food security, mitigate climate change, and protect coastal and inland ecosystems from further degradation if restored to a healthy, resilient state. To promote the restoration of soil in Hawaiʻi, it is vital that stewards of the land are able to observe changes in its health and develop a plan for integrating soil health management practices that are practical and efficient for the diversity of land use in Hawaiʻi. A method for quantitatively assessing a soil's health to ensure prevention of further soil degradation, and to guide restoration developed specifically for tropical soils in Hawaiʻi's natural and working landscapes, currently is lacking.

Hawaiian soil diversity spans soil taxonomy, current land use, historical land use, and climates, making a one-size-fits-all soil health score not useful, nor suitable. Similar to human health, the term soil health is relative to the applied context, and so an applicable definition of soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans" (NRCS, 2018). Like human health, soil health cannot be confined to one trait but rather it encompasses physical, chemical, and biological traits as well as the historical background of land use. A critical step in the development of a reliable and robust soil health test for Hawai'i requires the selection of a suite of appropriate soil health indicators sensitive to change in soil management.

2.2 OBJECTIVES AND HYPOTHESES

At present, there exists a list of potential soil health indicators for Hawaii, but it requires refinement and a robust test of its suitability for use across Hawaii's diverse soils and landscapes (Figure 2.1). With the overall goal of developing a robust soil health index appropriate for Hawai'i, two objectives and hypotheses were developed:

Objective 1: Identify patterns of land use and soil taxonomy that are associated to the changes in values of soil parameters and which could be indicative of soil health.

Objective 2: Refine a large suite of potential soil health indicators and identify the most sensitive indicators of differences in soil characteristics related to soil health in Hawai'i, across diverse soils and land use classes that are also practical for farmers and researchers to use.

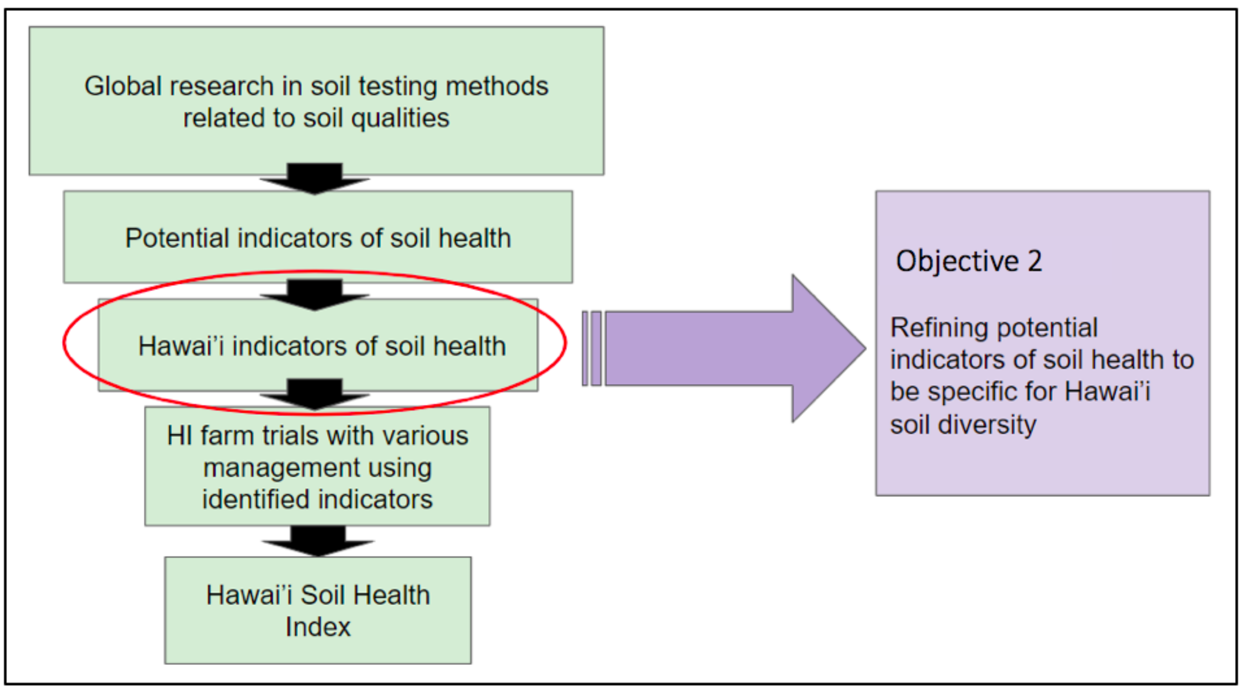


Figure 2.1 A visual representation of the stages of developing a soil health index, showing Objective 2 as the process of refining potential indicators of soil health from global research to indicators refined for Hawai'i.

Hypothesis 1: Level of intensity of agricultural activity is a main driver of differences in indicators representing measurements related to soil health due to correlated loss of soil organic matter and soil life measurements.

Hypothesis 2: Values of water stable aggregates, potentially mineralizable nitrogen, soil respiration, and bulk density are the strongest indicators of soil health, regarding their sensitivity to variability in soil management, due to their mechanistic relationship to organic matter content and soil life.

2.3 METHODS

2.3.1 Site selection

Selected site locations from cropland, grassland, and forest covered a range of soil management, fertility, and soil taxonomy diversity to maximize variance in the data related to soil health (Table 2.1). Soil samples from six soil orders were collected from 22 sites across the islands of Oahu, Maui, and Molokai, consisting of Oxisols, Ultisols, Andisols, Inceptisols, Vertisols, and Mollisols (Appendix B). While there is a considerable agriculture presence on the island of Hawaiʻi, no soil samples were included from there because of current restrictions on unsterilized soil transport due to precautions of spreading the Rapid ʻŌhiʻa Death fungal pathogen. Groups of management selected for sampling came from sites that were initially classified as either organic and conventional cropland, forest, pasture, or unmanaged land. At least three types of management made up each soil order sampled with as many sites as possible from the same soil series within each order to reduce variability. Land managers of each site were asked to share information on site management and land history. Their responses provided detail on irrigation, tillage, pesticide use, vegetation cover, fertilizer, current soil management practices, as well as details of management in short term and long term history (when available).

Table 2.1 The 22 site locations from cropland, grassland, and forest that were selected to cover a range of soil management, fertility, and soil taxonomy diversity spanning six soil orders across the islands of Oahu, Maui, and Molokai.

	Site ID	Elevation (meters)	Soil Order	Soil Series	Taxonomy	Current Management	Management History	Vegetative cover
Oahu	A	4	Mollisol	Waialua	Very-fine, mixed, superactive, isohyperthermic Pachic Haplustolls	Organic	Long term conventional agriculture 3yrs prior	Beet, cilantro, carrot
	B	8	Mollisol	Ewa	Fine, kaolinitic, isohyperthermic Aridic Haplustolls	Conventional	Long term conventional agriculture	Melon
	C	57	Oxisol	Lahaina	Very-fine, kaolinitic, isohyperthermic Rhodic Eutrustox	Unmanaged	Long term conventional agriculture 10yrs prior	Guinea grass, shrubbery
	D	56	Oxisol	Lahaina	Very-fine, kaolinitic, isohyperthermic Rhodic Eutrustox	Organic	Long term conventional agriculture 10yrs prior	Kale
	E	45	Oxisol	Lahaina	Very-fine, kaolinitic, isohyperthermic Rhodic Eutrustox	Conventional	Long term conventional agriculture	Corn
	F	57	Mollisol	Waialua	Very-fine, mixed, superactive, isohyperthermic Pachic Haplustolls	Unmanaged	Long term conventional agriculture 18yrs prior	Torpedo and guinea grass
	G	169	Oxisol	Wahiawa	Very-fine, kaolinitic, isohyperthermic Rhodic Haplustox	Unmanaged	Long term conventional agriculture	Torpedo and guinea grass
	H	235	Oxisol	Wahiawa	Very-fine, kaolinitic, isohyperthermic Rhodic Haplustox	Conventional	Long term conventional agriculture	Bok choi, lettuce
	I	35	Vertisol	Lualualei	Fine, smectitic, isohyperthermic Typic Gypsitorrerts	Organic	Animal husbandry followed by 20yrs fallow, 16yrs prior	Spinach, arugula
	J	29	Vertisol	Lualualei	Fine, smectitic, isohyperthermic Typic Gypsitorrerts	Conventional	Long term conventional agriculture	Green onion
	K	36	Vertisol	Lualualei	Fine, smectitic, isohyperthermic Typic Gypsitorrerts	Unmanaged	Long term conventional agriculture approx. 60yrs prior	Torpedo grass, halekoa, keawe
Maui	L	1182	Andisol	Kula	Medial, amorphic, isothermic Humic Haplustands	Conventional	Long term conventional agriculture	Cabbage
	M	408	Inceptisol	Haliimaile	Very-fine, parasesquic, isothermic Oxic Dystrustepts	Conventional	Long term conventional agriculture	Pineapple
	N	153	Inceptisol	Haliimaile	Very-fine, parasesquic, isothermic Oxic Dystrustepts	Pasture	Long term conventional agricutlure 3yrs prior	Signal grass, mixed volunteer grass
	O	369	Inceptisol	Haliimaile	Very-fine, parasesquic, isothermic Oxic Dystrustepts	Forest	Long term conventional agriculture approx. 40yrs prior	Eucalyptus, silver oak, guinea grass, shrubbery
	P	1314	Andisol	Kula	Medial, amorphic, isothermic Humic Haplustands	Forest	Forest, no known agriculture	Eucalyptus, shubbery, blackberry
	Q	1322	Andisol	Kula	Medial, amorphic, isothermic Humic Haplustands	Pasture	Agriculture approx. 100yrs prior	Kikuyu grass
	R	1392	Inceptisol	Amalu	Clayey, mixed, superactive, isothermic, shallow Histic Placic Petraquepts	Forest	Forest, no known agriculture	Koa, olapa, native vegetation
	S	679	Inceptisol	Haliimaile	Very-fine, parasesquic, isothermic Oxic Dystrustepts	Pasture	Set stock dairy 10yrs prior, possible cultivation 50yrs prior	Kikuyu and mixed pasture grass species
Molokai	T	225	Ultisol	Halawa	Very-fine, parasesquic, isothermic Ustic Haplohumults	Forest	Forest, no known agriculture	Kikuyu grass, christmas berry
	U	223	Ultisol	Halawa	Very-fine, parasesquic, isothermic Ustic Haplohumults	Pasture	Pasture	Mixed pasture grass, legume, guinea grass
	V	224	Ultisol	Halawa	Very-fine, parasesquic, isothermic Ustic Haplohumults	Organic	Pasture 6yrs prior	Kale, collards, onion

2.3.2 Soil collection

At each of the 22 sites, three field repetitions (plots) were collected for a total of 66 soil samples. Each plot sample was comprised of homogenized soil taken at the depth of 0-15cm from five soil cores using methods adapted from the Cornell Soil Health Manual (Moebius-Clune et al., 2016) and Doran et al. (1996) (Figure 2.2). The top surface of organic matter debris was carefully removed prior to soil coring. The 0-15cm depth zone of soil ecosystem is the most sensitive to changes in soil management and is therefore the chosen layer to measure sensitive indicators of soil health (Dick et al., 1996). Within the site, the three plots were at least 5 meters apart and selected to best characterize the property by judgement sampling, which takes into consideration potential differences in management practices and crop type (Dick et al., 1996). There was no strong evidence to expect high variance in the soil properties and so simple random sampling was sufficient in each 1 m^2 plot (Figure 2.2) (Dick et al., 1996).

Within each of the 66 plots, composite sampling was done by thoroughly mixing collected soils into one bulk sample per plot (Dick et al., 1996). Samples were transported back to storage facilities and frozen at -20°C as well as an air-dried portion (less than 10% moisture). Samples for phospholipid fatty acid testing were kept chilled, not frozen, and shipped immediately under refrigeration to the analysis facility.

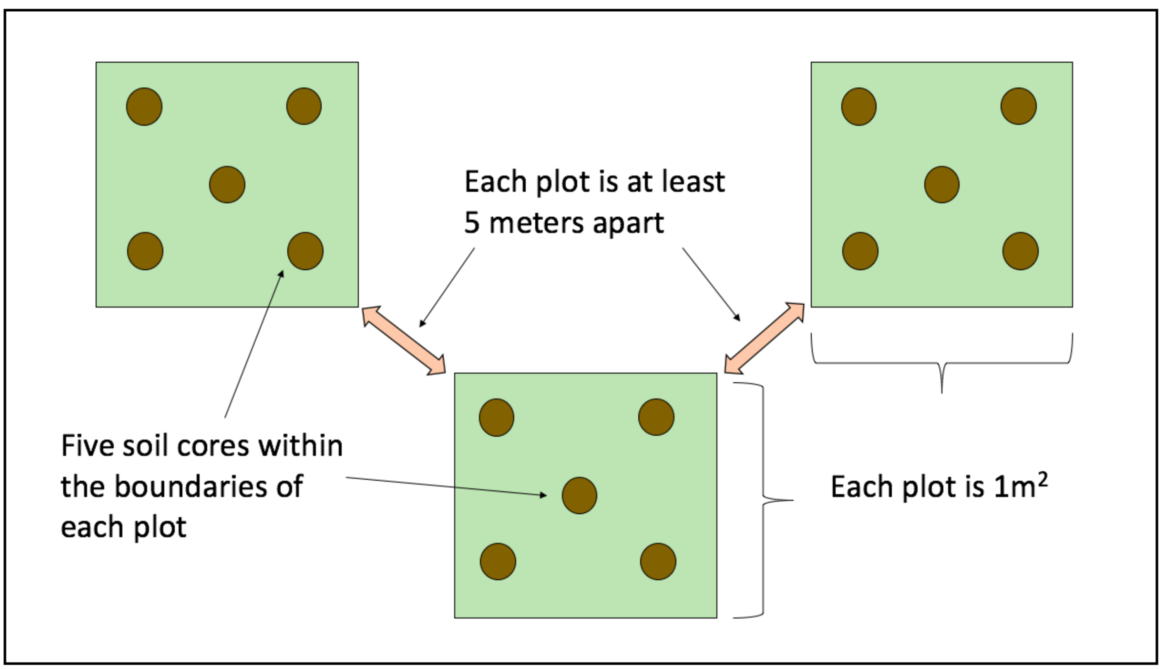


Figure 2.2 Field sampling design at each site for bulk soil collection, consisting of three plots at each site.

2.3.3 Soil analysis

Aggregate stability

Soils with higher water-stable aggregate stability have increased water infiltration, water storage, water and gas exchange, and resistance to erosion (Arai et al., 2014). Soil aggregates can store and protect organic carbon from being lost from the soil as a physical protection mechanism from microbes as well as restricting the diffusion of oxygen and enzymes (Blankinship et al., 2016, Berhe et al., 2012). Aggregate stability was determined by measuring water-stable aggregates via the wet-sieving method using the Eijkelkamp apparatus (Giesbeek, Netherlands), for macro-aggregate and 'mega-aggregates' (0.25-2 mm and 2-4 mm, respectively) (Figure 2.3). Air-dried samples were used for all soil samples except for Andisols, which, due to the known irreversible damage done to soil properties once dried, were only dried enough so that they could pass without force for dry-sieving aggregate size classes. A 4g sample of the dry-sieved soil aggregates was placed into a respective sieve size and wetted via capillary action for five minutes. The samples oscillated vertically (1.3 cm at 34 times/min) into 75 mL of distilled water for 10 minutes and then lifted out to briefly drain. Aggregates that are not water stable are collected in the water beneath the sieve and dried to 105°C and then weighed. Aggregates that are water stable remained on the sieve and were dispersed using 40 mL of a 2 g/L solution of either sodium hexametaphosphate (if soil pH is greater than 7) or sodium hydroxide (if soil pH is less than 7) and placed on a horizontal shaker table for 16 hours. After dispersion, the samples were again passed through their corresponding sieve size and water stable aggregates collected beneath the sieve, dried to 105°C, and weighed, with only rocks and organic matter remaining on the sieve. Samples with strong aggregates required mechanical dispersion by use of a rubber policeman attached to a stir rod and pushed through the sieve. Final values of water stable aggregates in the two size classes was calculated by subtraction of the dispersant precipitate from the water-stable aggregate dry weight, divided by the total dry weight of aggregates added to the sieve. Values are reported as percent water-stable aggregates by size class.

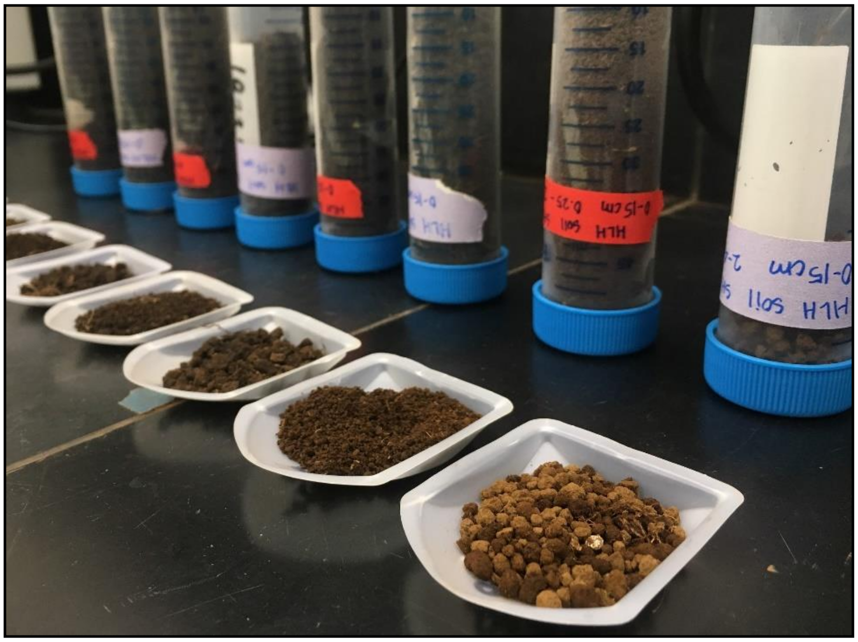


Figure 2.3 The air-dried soil aggregates of sizes 0.25-2 mm and 2-4 mm prior to wet-sieving.

Bulk density

Bulk density serves as a measure of the degree of soil compaction and hence potential restrictions upon root growth, as well as limitations in pore space for air and water to fill (Arshad et al., 1996). Density soil collections, conducted during field sampling, used a 5.4 cm diameter metal core cylinder with a volume of 68.7 cm^3 to collect a soil column at 10 cm depth (Figure 2.4). Cores were carefully inserted to insure minimal disturbance to obtain an uncompacted soil volume and the extracted soil volume was stored separately from the bulk soil collection. Bulk density samples were dried to 105°C, weighed, and then sieved. Rocks greater than 2 mm in size were removed, weighed, and their volume was measured via water displacement. Rock weights and volumes were subtracted from the total bulk density volume and weight values. Bulk density values are reported as g/cm^3.

Figure 2.4 Bulk density core carefully sampled at a depth of 10 cm.

Texture

Soil texture provides information on soil structure regarding rates of water infiltration, available pore space, and can also relate to soil fertility. Soil texture is an intrinsic soil property that is not affected by management. Texture values were obtained from the available National Resources Conservation Service (NRCS) online soil survey reports (Soil Survey Staff, NRCS-USDA, 2018) for each soil series. Texture values were reported in percent sand, silt, and clay.

Soil hardness

Soil hardness is the capacity of the soil to resist penetration by a rigid object and relates to the compactness of a soil as well as the cementing features of its mineral structure (Arshad et al., 1996). Compaction reduces the soil's ability to support root growth and reduces water infiltration, increasing the potential for erosion. A Fieldscout SC 900 (Spectrum Technologies, Aurora, IL) soil compaction meter (penetrometer) that applies vertical manual force was used to measure and record resistance in the field. The penetrometer was used at each of the 66 plots and values in kPa were recorded at each 2.5 cm increment to a maximum potential depth of 30 cm. At sites with high soil hardness, values were recorded until the probe could no longer move through the soil profile. Values for soil hardness are reported at the surface (0 cm) and at plow depth (15 cm). For soils that did not allow the probe to reach 15 cm depth due to excessive hardness, the value 5000 kPa was used to represent the maximum pressure observed across sites. Penetration resistance classes range from <10-8000 kPa and respectively represent soil with extremely low to extremely high soil hardness (Arshad et al., 1996).

Total organic C and N

High organic matter in the soil is known to correlate with various critical soil functions as well as increase a soil's resilience to drought and extreme rainfall and also may reduce nutrient inputs (Bot and Benites, 2005, Awale and Chatterjee, 2017). The total organic C measurement is highly correlated to organic matter content (Moebius- Clune et al., 2016). The Costech Elemental Analyzer (Costech Analytical Technologies, Inc., Valencia, CA, USA) provides the percent total carbon and nitrogen found in each sample. A soil subsample from each plot was dried to 105°C, ground to pass through a 250 μm sieve and acidified as necessary in an airtight container with hydrochloric acid and fumigated for four hours to remove inorganic carbon and samples were then measured in the elemental analyzer. The acidification stage is necessary for soils that have been limed to increase pH as well as those soils with parent material rich in calcium carbonate (coral). Values for total organic carbon and total nitrogen are reported as a percent of the dry soil mass.

pH

Soil pH is regarded as a standard measurement of soil because of its influence in essential nutrient availability and plant toxicity (Karlen et al., 2003a). Typically, a pH range of 6.0-7.0 is considered ideal, however, this is crop and ecosystem dependent. Soil pH values were obtained using a 2:1 method in water with a SympHony SB70P meter. The air-dried equivalent of 10 g soil was mixed into 20 mL distilled water, mixed on a Vortex shaker for 10 seconds, and allowed to sit for 30 minutes prior to measurement of the soil solution.

Extractable nutrients calcium, sodium, potassium, and phosphorus

Base cations and available phosphorus impact soil fertility and salinity, and ideal concentrations depend on crop or plant cover. A Mehlich III extraction measured calcium, sodium, potassium (Ca^{+2}, Na^{+}, K^{+}) and ortho-phosphate using 2.5 g of air-dried soil. The soil was weighed into 50 mL centrifuge tubes and 25 mL of Mehlich III was pipetted into each sample. Each sample shook for five minutes on a reciprocal shaker and then filtered through Whatman No. 2 filter paper. The extractant was immediately stored in a freezer, and thawed to room temperature before analysis. Ca^{+2}, Na^{+}, and K^{+} were analyzed using the flame photometry method, while ortho-phosphate was analyzed on a LACHAT 8500 Series 2 (Hach Company, Loveland, CO, USA) using the flow-injection colorimetric method read at 880 nm. Reported values for extractable nutrients are in mg/Kg soil.

Hydroxylamine hydrochloride extractable Fe/Al

The hydroxylamine hydrochloride extraction is used to remove amorphous minerals from soil by bringing them into solution, which is most meaningful to measure in soils such as Andisols composed of poorly and non-crystalline minerals (Chao and Zhou, 1983). This test is commonly used in formula with other metal element extractions for final parameter values that assist in taxonomic classifications of soils as well as carbon sequestration potential (Rasmussen et al., 2018). Using the procedure adapted from Carter and Gregorich (2008), air-dried samples were ground to pass through 150 µm mesh sieve, while Andisol samples were not dried and therefore were also not ground, due to the known irreversible damage done to soil properties once dried. A 0.1g soil sample was weighed into a centrifuge tube as well as 25 mL of 0.25M hydroxylamine hydrochloride and 0.25 M hydrochloric acid solution. Samples were placed on a shaker table for 16 hours and then centrifuged for 20 minutes at 1500 rpm. Next, the sample supernatant was filtered through Whatman 52 filter paper. The final filtered sample was analyzed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to measure the concentration of elements iron, aluminum, and silica with values reported in g/kg soil.

Citrate dithionite extractable Fe/Al

Citrate dithionite extractable elements are used most commonly to identify the amount of "free" secondary crystalline and short range order iron oxyhydroxides in soil by removing organically-complexed and amorphous iron, aluminum and silica as well as iron and aluminum oxides and bringing them into solution (Loeppert and Inskeep, 1996). The reducing environment created by the dithionite dissolves metallic oxides while the sodium citrate chelates the dissolved metals and buffers the pH to near 7 and prevents compound precipitation (Courchesne and Turmel, 2008). This test is commonly used in formula with other metal element extractions for final parameter values that assist in taxonomic classifications of soils as well as carbon sequestration potential (Rasmussen et al., 2018). Air-dried samples were ground to pass through 150 µm mesh sieve, while Andisol samples were not dried and therefore were also not ground, due to the known irreversible damage done to soil properties once dried. A 0.5 g soil sample, 6g sodium citrate 0.5 g sodium dithionite, and 30 mL deionized water are added to a centrifuge tube and shaken for 15 seconds before opening to ventilate and then placed on a reciprocating shaker for 16 hours. Next, 12 µl of polyacrylamide flocculating agent was added to each sample after transfer to a volumetric flask, mixed for 15 seconds and diluted to a 50 mL volume with deionized water. Each sample was poured back into centrifuge tube, and centrifuged at 1800 rpm for 30 minutes prior to filtering through Whatman 52 filter paper. Final filtered samples were analyzed by ICP-AES to measure the concentration of elements iron, aluminum, and silica with values reported in g/kg soil.

Sodium pyrophosphate extractable Fe/Al

The sodium pyrophosphate extraction is used to remove the organically-bound iron and aluminum, which often controls aluminum in surface horizons of mineral soils and O-horizons of organic matter-rich soils (Bloom et al., 1979, Walker et al., 1990). This test is commonly used in formula with other metal element extractions for final parameter values that assist in taxonomic classifications of soils as well as carbon sequestration potential (Rasmussen et al., 2018). Using the procedure from Carter and Gregorich (2008), air-dried samples were ground to pass through 150 µm mesh sieve, while Andisol samples were not dried and therefore were also not ground, due to the known irreversible damage done to soil properties once dried. A 0.025 g sample of soil was weighed into a centrifuge tube and 25 mL of 0.1 M sodium pyrophosphate was pipetted into each sample and then placed on shaker table for 16 hours and centrifuged for 15 minutes at 20,000 G. Each sample was filtered through Whatman 52 filter paper, and the collected supernatant sample was analyzed by ICP-AES to measure the concentration of elements iron, aluminum, and silica with values reported in g/kg soil.

Hot water extractable C and N

Water extractable carbon and nitrogen measurements reflect changes in the labile pools of soil organic matter caused by management practices (Hamkalo and Bedernichek, 2014). Extractable carbon is associated with aggregate formation as well as a reserve of nutrients and energy for plants and microbes, while extractable nitrogen is readily mineralizable nitrogen that impacts plant growth (Hamkalo and Bedernichek, 2014, St. Luce et al., 2016). Hot water extractable carbon is associated with biological activity as the hot water lyses microbe cells and releases biomass components, which relates well with microbial biomass C (Sparling et al., 1998, Ghani et al., 2003). Using methods adapted from Ghani et al. (2003), modified from Haynes and Francis (1993), a 3g oven-dried equivalent sample of air-dried soil was placed into 30 mL of room temperature distilled water and placed on horizontal shaker table for 30 minutes, centrifuged at 3000 rpm for 20 minutes and then filtered through a pre-leached 45 µm acetate cellulose syringe filter. The collected supernatant was acidified with 75 µL of 1M HCl before being stored frozen until analysis as the “cold water extraction.” Another 30 mL distilled water, corrected by weight for any water still remaining in the soil pellet, was added to the sample and shaken on a vortex shaker for 10 seconds, and placed into hot water bath at 80°C for 16 hours. Tubes were then vigorously shaken for 10 seconds to re-suspend the hot-water extractable carbon and nitrogen, centrifuged for 20 minutes at 3000 rpm and again filtered through a pre-leached 45 μm acetate cellulose syringe filter and stored frozen until analysis as the "hot water extraction." Hot and cold water samples were thawed to room temperature and analyzed for total organic carbon and nitrogen using the Total Organic Carbon (TOC) Analyzer model 5000A (Shimadzu Corporation, Kyoto, Japan). Dissolved organic carbon is the sum of cold and hot extractable values. Results are reported in μg C/g soil and μg N/g soil. Hot water extractable inorganic nitrogen was measured for ammonium and nitrate on a LACHAT 8500 Series 2 (Hach Company, Loveland, CO, USA) using the flow-injection colorimetric method read at 660nm for ammonium and 520 for nitrate.

Water holding capacity

A soil's ability to hold water is vital for sustained plant growth and supporting microbial life and is often correlated to soil texture, amount of soil organic matter, as well as bulk density (Brady and Weil, 2008). Higher values of water holding capacity are ideal for a healthy soil ecosystem. Using an adapted protocol from Awale and Chatterjee (2015), the air-dried equivalent of 10 g oven-dried soil was added to a 50 mL cylinder, with an attached Whatman #54 filter on the bottom acting to contain the soil placed into the tube. Tubes were lowered into water for capillary action to saturate the soil column. Once all soils had reached saturation, they were drained for one hour and reweighed to calculate their full water holding capacity. Water holding capacity was calculated as the weight of the water retained in the soil divided by the oven dry weight of the soil, reported in percent.

24-hour soil respiration (CO_2 burst)

Soil respiration methods measure the metabolic activity of the microbial communities in the soil, an important aspect of soil fertility (Haney et al., 2008). Greater respiration of the microbes in soil is indicative of greater activity of the soil microbes present which contribute to organic matter decomposition and nutrient cycling (Haney et al., 2008). A 24 hour CO_2 release highly correlates with other methods of soil respiration, such as microbial biomass, yet is a simpler and easier to use method than older test methods (Haney et al., 2008). To measure soil respiration, a 25 g oven-dry equivalent sample of air-dried soil was rewetted to 60% water holding capacity, placed into a 610 mL airtight container at a controlled temperature of 25°C for 24 hours, and the carbon dioxide respiration emissions were captured and measured in a PerkinElmer Clarus 580 GC (PerkinElmer, Waltham, MA, USA). Final reported values were converted into µg C/g soil.

Carbon mineralization incubation

The availability of carbon to be metabolized by soil microbes and released as CO_2 is regulated by various physical, chemical, and biological soil properties. The labile C, or rapid turnover C, can be a sensitive measurement of changes in soil organic carbon stocks that influence soil health (Awale et al., 2017). Soils prepared for the 1-day soil respiration test (see soil respiration methods above) were left open to the atmosphere for three days to freely exchange atmospheric gas, capped and allowed to continue the incubation at 25°C for a period of 119 days (4 months). The containers were sampled for CO_2 at different time points depending on the amount of CO_2 emitted to avoid toxic levels of CO_2 buildup within the container. Soils with high microbial activity were sampled 1-2 times a day for the first three months and then 3-4 times per week near the end of the 119 days. These highly microbially active soils also underwent a reduction to ⅓ the original soil mass at 90 days. Less active soils were initially sampled 1-3 times a week and then once every two weeks up to day 119. Soils were moisture corrected to maintain the moisture content within 5% the original water content. The values were modeled in R at incubation days 1, 3, 7, 14, 30, 60, 90, 119 for carbon pool identification. Final reported values are the percent of total carbon that was mineralized and respired over 119 days as the closest estimate to a labile pool (cumulative gas concentrations were converted into a carbon mass and divided by total initial carbon mass).

Microbial community - PLFA

Phospholipid fatty acids (PLFA) are a key component of microbial cell membranes and analysis of PLFA provides a snapshot of microbial community structure representing the biological soil response to changes in land management (Zelles et al., 1995). Buyer's high-throughput method of analysis is chosen over other options representing microbe diversity because of its speed to produce results and because it is a reliable adaptation of older methods such as Bligh and Dyer's (1959) extraction methods (Buyer et al. 2012). Refrigerated and never-frozen soil samples were packed on dry ice and sent to an outsourced lab for PLFA analysis according to the extraction method of Buyer and Sasser (2012). Values reported for total PLFA (in pmol/g dry soil) are robust estimates of microbial biomass (Tunlid and White, 1992; Zelles et al., 1995). In addition to overall microbial biomass, the analysis produced estimates for the following microbial groups; gram positive, gram negative, anaerobe, actinomycetes (Actinobacteria), methanobacter, fungi, and AM fungi.

Enzyme extractions

Nutrient cycling in soils relies not only on direct nutrient inputs, but also on the ability of soil enzymes to decompose organic matter and release nutrients into plant available forms. Soil enzymes are substrate-specific and during reaction with the substrate, release the corresponding product into the soil ecosystem (Alkorta et al., 2003). Enzyme activity does not necessarily correlate with live soil microbes and can source from dead microbes, residues, and animals (Tabatabai, 1994). Hence, concentrations of soil enzymes can estimate long term microbial activity and respond to changes in soil management more quickly than many other indicators that slowly degrade such as total carbon loss (Dick et al., 1994). The enzyme β-glucosidase is important for recycling carbon compounds into energy for microbes and is a reliable predictor of organic matter decomposition (Alkorta et al., 2003). β-glucosaminidase is involved in both carbon and nitrogen mineralization while acid phosphatase is responsible for the recycling of phosphorus, both important cycles related to nutrient uptake by plants (Parham and Deng, 1999, Alkorta et al., 2003). β-glucosidase, β-glucosaminidase, and Acid phosphatase were separately extracted from each soil sample and each extraction followed protocols outlined in Tabatabai (1994), Parham and Deng (2000), and Acosta-Martinez and Tabatabai (2011), respectively. A pre-sieved (<2 mm) 0.5 g sample of air-dried soil was mixed with reagents and incubated at 37°C for one hour. The reaction was then stopped and the samples were filtered. The filtered supernatant was measured for intensity of yellow color in a 6405 UV/Vis Spectrophotometer (Jenway, Staffordshire, UK) and results are reported in μg p-nitrophenol/g soil.

Potentially mineralizable N

The conversion of nitrogen from complex organic forms into ammonium (mineralization) is a biological process in which nitrogen becomes plant available. Nitrogen in the soil stored in various forms of organic matter, such as crop residue, is not all plant available. Instead, nitrogen is mostly in the form of complex organic molecules such as proteins, which are too large for plant uptake (Moebius-Clune et al., 2016). Various microbial groups oxidize these molecules into ammonium and nitrate by mineralization and nitrification which are then in plant available forms (Moebius-Clune et al., 2016). Thus, measurement of nitrogen mineralization is an estimate of the capacity of the soil microbes to recycle nitrogen into plant available forms (Moebius-Clune et al., 2016). The potentially mineralizable nitrogen protocol used is adapted from the methods of Drinkwater et al. in a seven-day anaerobic incubation, as a more practical measurement than long incubation methods (1996).

Soil samples undergo a pre-measurement as a baseline of ammonium present in the soil as well as a post-incubation measurement to determine the amount of ammonium mineralized. For each soil sample, two 8 g samples of sieved (2 mm) field moist soil (thawed from frozen) were placed into 50 mL centrifuge tubes labeled as pre and post samples. After weighing, 40 mL of 2 M potassium chloride (KCl) was added to each pre tube, horizontally shaken on a shaker table for one hour, filtered through #42 Whatman paper, and the filtered supernatant was frozen until analysis. The post sample for each soil was prepared for incubation by pipetting 10 mL of distilled water into each tube and was placed in a dark incubation chamber at 30°C for seven days. After incubation, 30 mL of 2.67 M KCl solution was added to each post tube (to equal a 40 mL solution of 2 M KCl), horizontally shaken on a shaker table for one hour, filtered through

#42 Whatman paper, and the filtered supernatant was frozen until analysis. All samples were analyzed for ammonium using a LACHAT 8500 series 2 using the flow-injection colorimetric method read at 660 nm. The net ammonium mineralization or immobilization is equal to the ammonium value after the incubation period minus the ammonium value of the pre-incubation, and reported as mg NH_4-N/kg.

Microbial functional diversity - Amplicon sequencing

Microbial functional diversity data provides a snapshot of the structure and metagenomic details of soil microbial communities, which fulfill many vital roles in soil health such as nutrient mobilization, immobilization, organic matter decomposition, and gas exchange (Soliman et al., 2017). Amplicon sequencing requires soil samples to be stored frozen until processing and processed as soon as possible to best represent a snapshot of the microbial populations. DNA was extracted from 10 g of soil per sample and prepared for polymerase chain reaction (PCR). The final amplified products are sequenced and provide data on the taxonomic diversity as well as abundance of microbes in each sample (Nguyen et al., 2015). Soils were preserved and prepared for amplicon sequencing, however, due to the time intensive nature of this indicator test, the data was not suitable for a reasonable soil health test and the completed data will be analyzed at a later time when it is made available. The process will sequence bacterial 16, fungal ITS, and eukaryotic 18S (for protists and nematodes) genes.

Arthropod richness and diversity

Arthropod populations in soils are a relatively simple bio-indicator assessment of soil life. Invertebrate communities are highly sensitive to disturbance due to their complex interactions with other soil life and their relative immobility from their soil environment (Menta, 2012). To determine arthropod richness and diversity, approximately 100 g of fresh soil (collected that day) was placed into the top chamber of a Berlese funnel and placed under a heat source. The soil sample's live arthropods migrate down away from the heat through a mesh into ethanol, where they are preserved to be counted and identified under a microscope to determine the arthropod richness and diversity.

2.3.4 Data analysis

Principal Component Analysis (PCA)

Data was prepared for Principal Component Analysis (PCA) in PC-ORD version 7 (Wild Blueberry Media LLC, 2018), a multivariate analysis program originally designed for ecologists (McCune and Mefford, 2018). PCA was selected because it is an ideal tool for reducing many variables of a dataset into a smaller set of summary variables. The procedure identifies patterns of redundancy, which meets the primary objective to reduce a large number of soil health indicators to a subset of robust and sensitive indicators as a MDS (Appendix E) (Peck, 2016, Andrews et al., 2002b).

As described by Peck (2016), PCA operates with a linear modeling approach to reduce many responses down to a group of best fit predictor variables. The process of PCA and the options selected can be summarized in the following steps: 1) calculation of a cross products matrix among all variables using a Pearson's correlation, and within it, Euclidean geometry and linear algebra to identify strong linear trends, 2) construction of the best linear fit through the multidimensional space created by each variable, where each sample point exists, creating axes of ordination by a form of matrix algebra called 'eigenanalysis,' 3) use of the eigenanalysis process to calculate eigenvalues (latent roots of the best fit equations) and eigenvectors (the linear combination coefficients on each axis), 4) construction of an eigenvector matrix scaled to its standard deviation, whose values are equivalent to the correlation coefficients between variables and axes, and finally, 5) eigenvalues in a randomization test report the number of statistically significant axes of analysis.

The final analysis from PCA ordination provides a list of axes by diminishing importance constructed from the redundant patterns of variable data, and the correlation coefficients of each variable to the dominant axes. The sum of the eigenvalues equals the number of variables provided, and the axis with the highest eigenvalue is the dominant axis. As a result, each axis explains a known portion of variance in the data and each has associated strengths to the variables tested (eigenvectors). To ensure a robust analysis, there should be more sample units than variables, and variables should be normally distributed with few zeros and low skewness. Data for the PCA ordination is derived from quantitative values provided in a main matrix, and categorical data in a secondary matrix can overlay the ordination as explanatory environmental data. For example, pH is a variable in the main matrix while the soil order of the sample is a secondary matrix variable.

Data preparation for PCA

All untransformed data (30 soil indicators) was run in a PCA for initial assessment of data distribution and corrected for skewness as needed. Uneven distribution of data in the 2D output suggested problematic skewness and the need to transform data which was confirmed by assessing distribution tables of each variable for non-normality (Appendix C). Outliers were assessed and noted at this stage and a test of skewness for each variable was performed in R. The data was considered highly skewed if a skewness value was above +1 or below -1, and moderately skewed if between +0.5 to -0.5. The data was symmetric and considered normally distributed if the skewness value was zero. Normal distributions are ideal for accurate PCA results and those that are highly skewed require transformation. Histograms visually presented the type of distribution for variables whose skewness was greater than |1| to guide the selection of transformation. Transformations of log, cube root, and square root were tested on each highly skewed variable since all were either positively or negatively skewed with single peaks. Transformed variables were rerun for skewness and the transformation with the lowest skewness value was selected as the best possible transformation (Table 2.2). A new PCA using transformed variables showed an improved graphical display regarding spatial distribution of plots and outlier assessment (Appendix C). The previous outliers were no longer present and the current plots flagged as outliers (exceeding two standard deviations) did not appear as visual outliers nor were clustered, and were kept in the dataset.

Table 2.2 A comparative list of skewness values among selected potential soil health indicators, untransformed and transformed to improve data normality, and the transformation technique used for maximum skewness improvement (if applicable).

Variable	Untransformed Skewness Value	Transformed Skewness Value	Transformation Method
pH	-0.89	-0.89	N/A
Bulk density	-0.73	-0.73	N/A
Hardness at 0cm	2.55	-0.13	Log base 10
Hardness at 15cm	0.95	0.95	N/A
Water holding capacity	2.07	1.51	Log base 10
Calcium	1.75	0.66	Square root
Sodium	2.18	0.43	Cube root
Phosphorus	3.84	-0.31	Log base 10
Potassium	0.6	0.6	N/A
Hot water extractable OC	4.06	0.48	Log base 10
24 hr CO2 Burst	2.33	0.5	Log base 10
PLFA	2.54	0.47	Log base 10
Crystalline Fe	0.28	0.28	N/A
Noncrystalline Al/Fe	2.07	1.22	Log base 10
% Total OC	2.31	0.77	Log base 10
% Total N	2.18	0.82	Log base 10
% Sand	1.88	1.33	Log base 10
% Silt	-0.87	-0.87	N/A
% Clay	-0.81	-0.81	N/A
C:N	0.53	0.53	N/A
Betaglucosidase	1.07	-0.44	Log base 10
Betaglucosiminidase	1.15	-0.25	Log base 10
Acid Phosphatase	2.59	0.021	Log base 10
Potentially mineralizable N	4.33	0.83	Cube root
Total dissolved OC	4.06	0.065	Log base 10
Total dissolved N	3.59	0.74	Log base 10
Inorganic N (hot water)	3.29	0.15	Log base 10
Water stable macro aggregates	-0.66	-0.66	N/A
Water stable mega aggregates	-0.0028	-0.0028	N/A
C mineralized in 4 months	1.81	-0.27	Log base 10

Verification of data balance and impact of potential outliers

Assessment of variable balance in PCA ordination compared various layers of explanatory data with parameters in a priori groupings consisting of biological, chemical, and physical soil properties (Stefanoski et al., 2016). Datasets in PCA can potentially be biased and skewed by variable selection and so were reviewed before beginning analysis. Values from the 30 measurable parameters served as the main dataset for PCA ordination and balance in groups was confirmed so that chemical, physical, and biological groups were all well represented in the list of included parameters. Overlays of supplemental environmental data operated as the second matrix and included land cover, historical disturbance, soil order, and soil series. Potential outlier sites and groups (e.g., the unique group of Inceptisols at Site R) were individually removed and re-added to determine their influence on the PCA and assess any significant impact on results. Second matrix overlays were used to identify potential issues with the distributions of data balance or flag potential errors in data manipulation.

Reduction of potential indicators

After PCA, the potential indicators were further assessed and reduced according to a list of variable reduction techniques. Quantitative and qualitative removal of variables was determined using the following criteria adapted from methods proposed by Karlen et al. (2001) and Andrews et al., (2002b): 1) "strong" sensitivity to data variance, where indicators with less than 68% correlation to the PCA axis of greatest variance explained are removed (Taylor, 1990), 2) robust practicality of measurement to process in a routine soil health test, where the indicator is removed if field measurements require expert skill to collect, or excessive labor or cost to perform, and lastly, 3) limited multicollinearity with other variables of similar critical soil function, where practicality between indicators is assessed if R^2 value between them is greater than 0.80.

2.4 RESULTS & DISCUSSIONS

2.4.1 Excluded indicators

Carbon pools, microbial functional diversity, and arthropod populations were not included in the final data analysis. Values from the carbon mineralization incubation were modeled in R at incubation days 1, 3, 7, 14, 30, 60, 90, 119 for carbon pool identification. However, many soils with high microbial activity and carbon content did not develop the required pool inflection points during the four-month incubation period, and so accurately modeled pools could not be determined due to insufficient data. The microbial functional diversity test is time and labor intensive, and so samples were unable to be processed for amplicon sequencing during the allotted data collection period in time to be included for analysis. The test for arthropod richness and diversity using Berlese funnels was also excluded from consideration for a soil health test. Due to inter-island travel and lack of facilities on site for the funnel setup, this method was only conducted for samples collected on Oahu. The Berlese funnel did not produce a reliable invertebrate count data, as the cropland soil's high friability led to incompatibility with the experimental equipment with too much soil falling into the ethanol solution. The arthropod indicator test was not implemented into the analysis due to the significant gaps in sample data, and not recommended for future use due to complications with soil friability. Final variables confirmed to be suitable in PCA showed balance among biological, physical, and chemical groups (Table 2.3) (Appendix E).

Table 2.3 The list of potential soil health indicators to be used for PCA in their corresponding soil characteristic groups regarding a measurement of a primarily physical, chemical, or biological soil characteristic.

Potential Indicators of Hawaii Soil Health

Measured parameters of soil health span physical, chemical, and biological aspects of soil

Physical	Chemical	Biological
Texture (Sand, silt, clay)	Total organic C and N	24 hr soil respiration
Bulk density	Hot water extractable N	Phospholipid fatty acids (PLFA)
Gravimetric water holding capacity	Nutrients (Ca^{+2}, Na^{+}, PO_4^{3-}, K^{+})	β-glucosiminidase
Water-stable aggregates (0.25-2mm)	C:N	β-glucosidase
Water-stable aggregates (2-4mm)	pH	Acid Phosphatase
Surface hardness	Crystalline Fe-oxides	Potentially mineralizable nitrogen
Subsurface hardness	Poorly and non-crystalline Fe/Al	Carbon mineralization
	Total dissolved nitrogen	Hot water extractable C
	Dissolved organic C	

2.4.2 Expanding site description groups

Land use groups

At the outset, four land use categories were established (organic cropland, conventional cropland, grassland, and forest). These groups were selected to capture the diversity of soil function in Hawai‘i, and historic and current site management data from land managers captured land use history. However, to more accurately describe similarities and differences relating to land use, “organic” and “conventional” groups were placed as sub-categories under broader land cover described as “cropland.” The land covers “grassland” and “forest” remained as is for a total of three land cover groups. However, the site characteristics within forest and grassland

land cover groups varied greatly, giving rise to the need for further division of forest and grassland land cover groups into management subcategorization as well.

Subcategorization of land cover groups using current and historic management

Using questionnaire responses from current land managers, site descriptions were compiled to supplement the original classification of sampled sites to include six management subgroups beneath cropland, forest, and grassland categories. Site data for subcategorization was limited to information that was available at all sites and included current management practices (tillage, addition of pesticides/herbicides/fertilizers, type of agriculture or vegetation) and time under the current management, historic practices (tillage, addition of pesticides/herbicides/fertilizers, type of agriculture or vegetation) and estimated time frame of that management, and land use transformations pertaining to significant land disturbance, restoration, or ownership.

Some of the forest and grassland locations included sites with a common history of previous intensive agriculture, while others had been under protective or long term management without a history of intensive agriculture. The grassland and forest sites with a history of previous agriculture were unlike the undisturbed forests, and were renamed to the more descriptive title ‘unmanaged previous intensive agricultural land,’ or UPIAL. Some sites in the forest category were further divided by dominant forest species covers. Forest sites were sub-categorized as either UPIAL, protected non-native, or protected native. Grasslands were also sub-categorized as UPIAL or pasture with no known history of disturbance. Sites were assigned accordingly to the best fit subcategorization (Table 2.4).

Table 2.4 Land cover split sites clearly into either cropland, grassland, or forest and sites were further divided into their descriptive management groups using available current and historic site data.

Land Cover	**Current Management**	**Description**
Cropland	Organic	No use of chemical pesticides, herbicides, or synthetic fertilizers
	Conventional	Use of chemical pesticides, herbicides, and synthetic fertilizers
Grassland	Unmanaged grassland from previous intensive agricultural land (UPIAL)	Previously agriculture-intense land with no current management system, grassland as dominate cover
	Pasture	Managed with pasture grasses for rearing livestock
Forest	Unmanaged grassland from previous intensive agricultural land (UPIAL)	Previously agriculture-intense land with no current management system, forest as dominate cover, and less than 100 years no disturbance
	Protected, non-native	Managed to preserve long-term non-native forest, greater than 100 years no disturbance
	Protected, native	Managed to preserve long-term native forest, greater than 100 years no disturbance

The overall reconstruction of site groupings produced a hierarchy of labeling that painted a more complete picture of what had happened over time in each group in addition to current management. Land cover split sites clearly into either cropland, grassland, or forest and were further divided into their descriptive management groups (Figure 2.5).

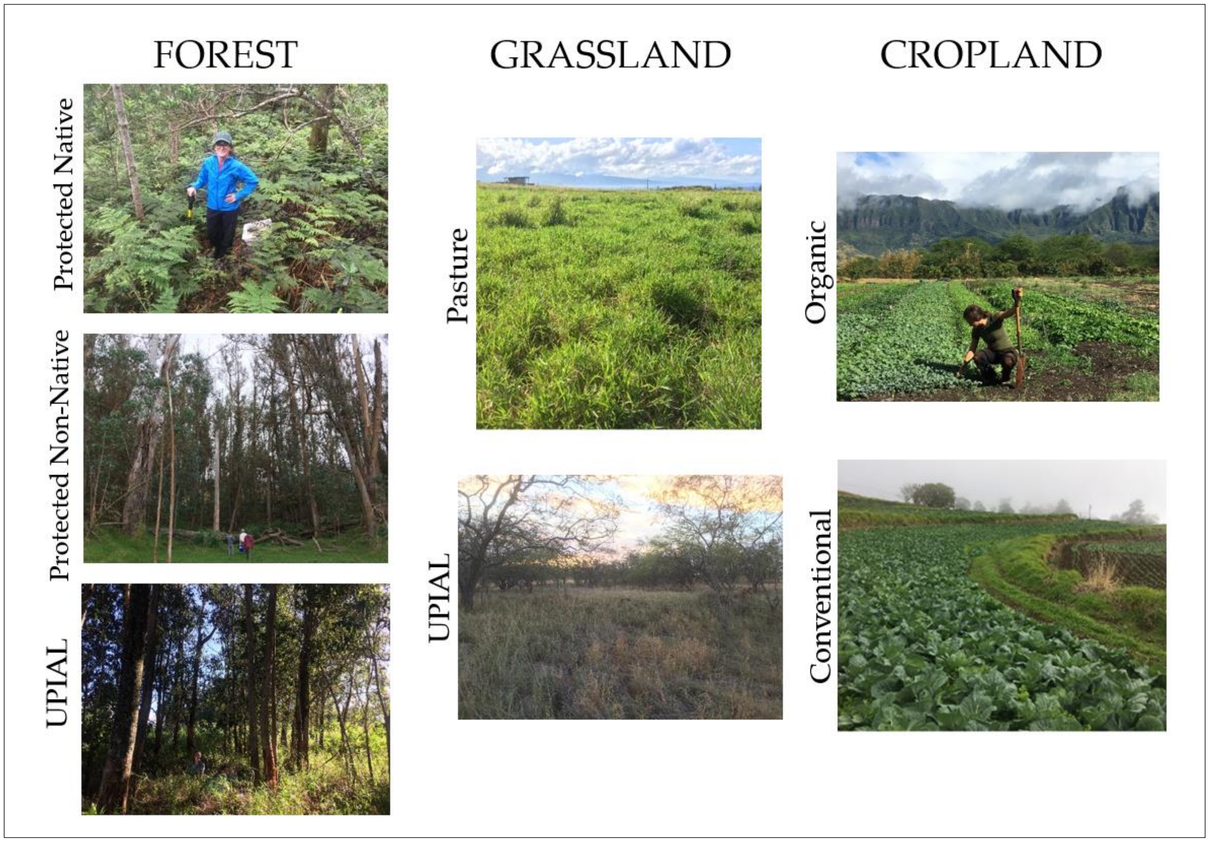


Figure 2.5 Images from field sites in each category of land management, separated by land cover (forest, grassland, or cropland). Unmanaged previous intensive agriculture land is represented by the acronym ‘UPIAL’.

Disturbance level as an additional categorization of sites

After accounting for the importance of previous land use on the soil variability, an index for categorizing disturbance added another level of difference among sites. Each site’s level of disturbance was identified based on the available history. Level of disturbance was based upon the degree of physical disruption of the soil structure and ecosystem, such as tillage or compaction (Table 2.5). The sub-categorization of management and the creation of a disturbance layer were not utilized in the PCA ordination and hence had no impact on data variance, but rather, was used to identify patterns of change in sites using descriptive information provided by land managers.

Table 2.5 Assessment of level of disturbance for each study site is categorized based on the time frames described since the most recent soil disturbance, based on available history of land use.

Level of Disturbance	**Description**	**Example**
Low	At least 50 years no disturbance	Forest with no cultivation history
Medium	Disturbed in the last 50 years, greater than 10 years no disturbance	Unmanaged land that was previously in crop production 20 years ago
High	Disturbed in the last 10 years, greater than 3 years no disturbance	Pasture that was tilled 5 years ago and no disturbance since
Very High	Disturbed in last 3 years	Currently tilled for seasonal crop production

2.4.3 Site distributions and patterns in PCA

Significant axes and variance extracted

The PCA output determined four significant axes, which cumulatively explained 75% of the data variance (Table 2.6, Table 2.7). As the major axis, Axis 1 represents the greatest variability explained within the data (43%), in contrast to Axes 2, 3, and 4 (explaining 16%, 9%, and 7% of data variability, respectively) (Table 2.7). As a result of the exploratory nature of PCA, there are no clear rules of interpretation, however, many methods are discussed among PCA users. Typically, an axis percentage of variability explained above 60% is used to support deductions, however, this value is a guideline and the ordination can still be interpreted without reaching 60% with the assistance of environmental data patterns (Dr. JeriLynn Peck, personal communication, May 4, 2018). Axes representing less than 10% of data variability or those axes with no clear associations to available second matrix groups are often regarded as only of nominal usefulness as a tool to explore trends and patterns. No such patterns were observed in the PCA ordination in relation to the 3rd and 4th axis (both less than 10%) and so are not graphically displayed in this analysis.

Table 2.6 Randomization results from the PCA output are used to determine the number of significant axes for interpretation, with the first four axes considered significant (p-value < 0.05).

RANDOMIZATION RESULTS
999 = N = number of randomizations

Axis	Eigenvalue from real data	Eigenvalues from randomizations: Minimum	Average	Maximum	p *	n
1	12.767	2.2110	2.5320	3.2502	0.001000	0
2	4.7141	1.9817	2.2851	2.6839	0.001000	0
3	2.7354	1.8919	2.1018	2.3760	0.001000	0
4	2.1747	1.7321	1.9504	2.1879	0.004000	3
5	1.5219	1.6194	1.8089	2.0371	1.000000	999
6	0.99314	1.5161	1.6894	1.9552	1.000000	999
7	0.79311	1.4074	1.5770	1.7414	1.000000	999
8	0.75096	1.3143	1.4723	1.6421	1.000000	999
9	0.64640	1.2234	1.3711	1.5362	1.000000	999
10	0.58462	1.1183	1.2797	1.4495	1.000000	999

Table 2.7 Variance extracted results report the percent of variance explained per axis as well as cumulatively. A cumulative total of 74.6% data variance is explained from the four significant axes (Table 2.6).

VARIANCE EXTRACTED, FIRST 10 AXES

AXIS	Eigenvalue	% of Variance	Cum.% of Var.	Broken-stick Eigenvalue
1	12.767	42.555	42.555	3.995
2	4.714	15.714	58.269	2.995
3	2.735	9.118	67.387	2.495
4	2.175	7.249	74.636	2.162
5	1.522	5.073	79.709	1.912
6	0.993	3.310	83.020	1.712
7	0.793	2.644	85.663	1.545
8	0.751	2.503	88.167	1.402
9	0.646	2.155	90.321	1.277
10	0.585	1.949	92.270	1.166

The PCA indicator vectors showed the most loading in a negative correlation to Axis 1, and a smaller group of indicators evenly loading positively and negatively for Axis 2 (Figure 2.6). The top five strongest indicators in each Axis direction (if available) showing greater than 35% correlation to that axis (representing at least a moderate correlation) are shown in Figure 2.6 (Taylor, 1990). Values that strongly pull data to the left of Axis 1 are those closely tied to soil carbon and life (e.g., PLFA, % total carbon, soil respiration). Some inherent indicators such as texture and iron oxides pull data to the right on Axis 1, as well as bulk density increasing in this opposite direction of increased life and carbon. Strong indicators pulling data upwards are nutrient-related, while mostly inherent and structure-related indicators separating some data downwards.

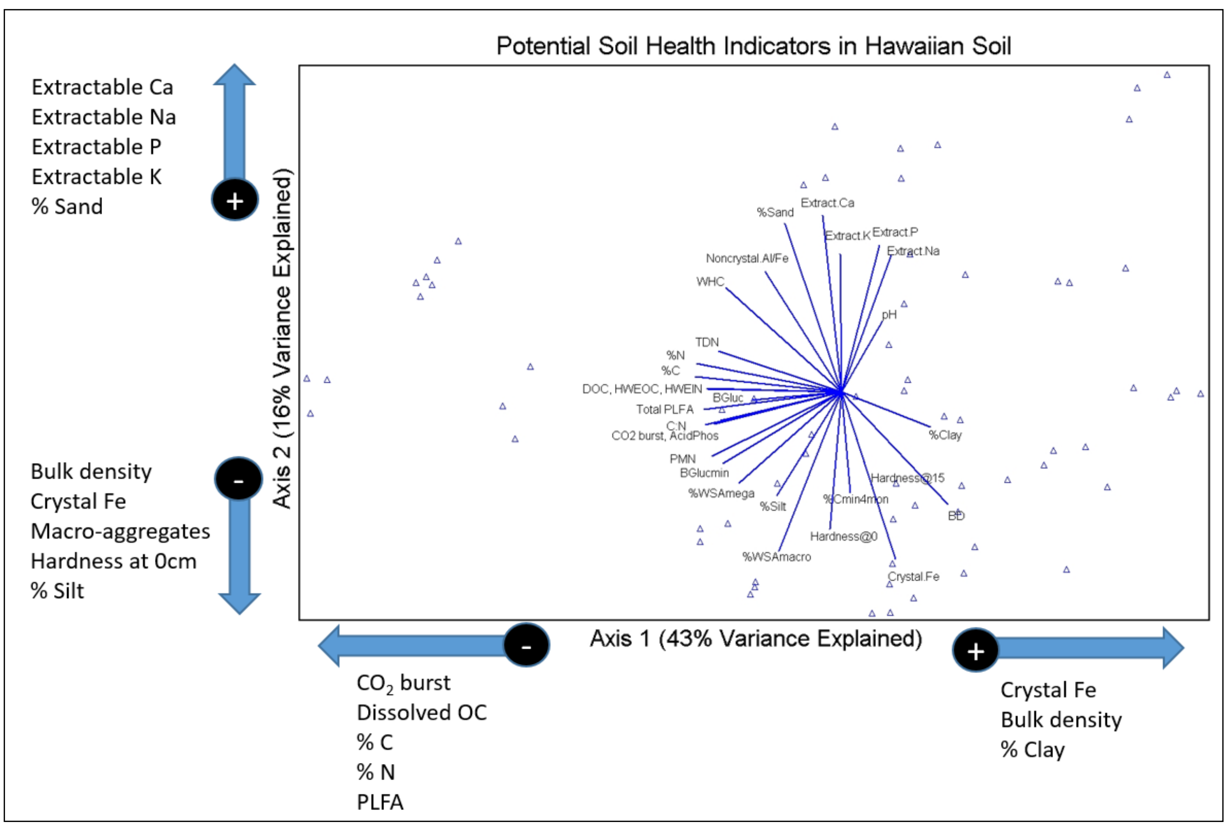


Figure 2.6 PCA ordination of all plots and all potential soil health indicators displaying the top five most correlated variables to each axis (> |0.35| correlation), for both positive and negative correlations.

PCA with land cover

The three land cover groups showed a trend of clear separation when overlaid as the second matrix data, with considerable overlap between forest and pasture, and pasture and cropland, and no overlap between forest and cropland (Figure 2.7). Figure 2.8 demonstrates the remaining overlap between land cover groups in 3D space. Generally, sites transition horizontally into these groups in alignment with major Axis 1. However, within each land cover group there is still high variability as expected. Examining subcategorization groups of land use next allows for greater explanation of such differences.

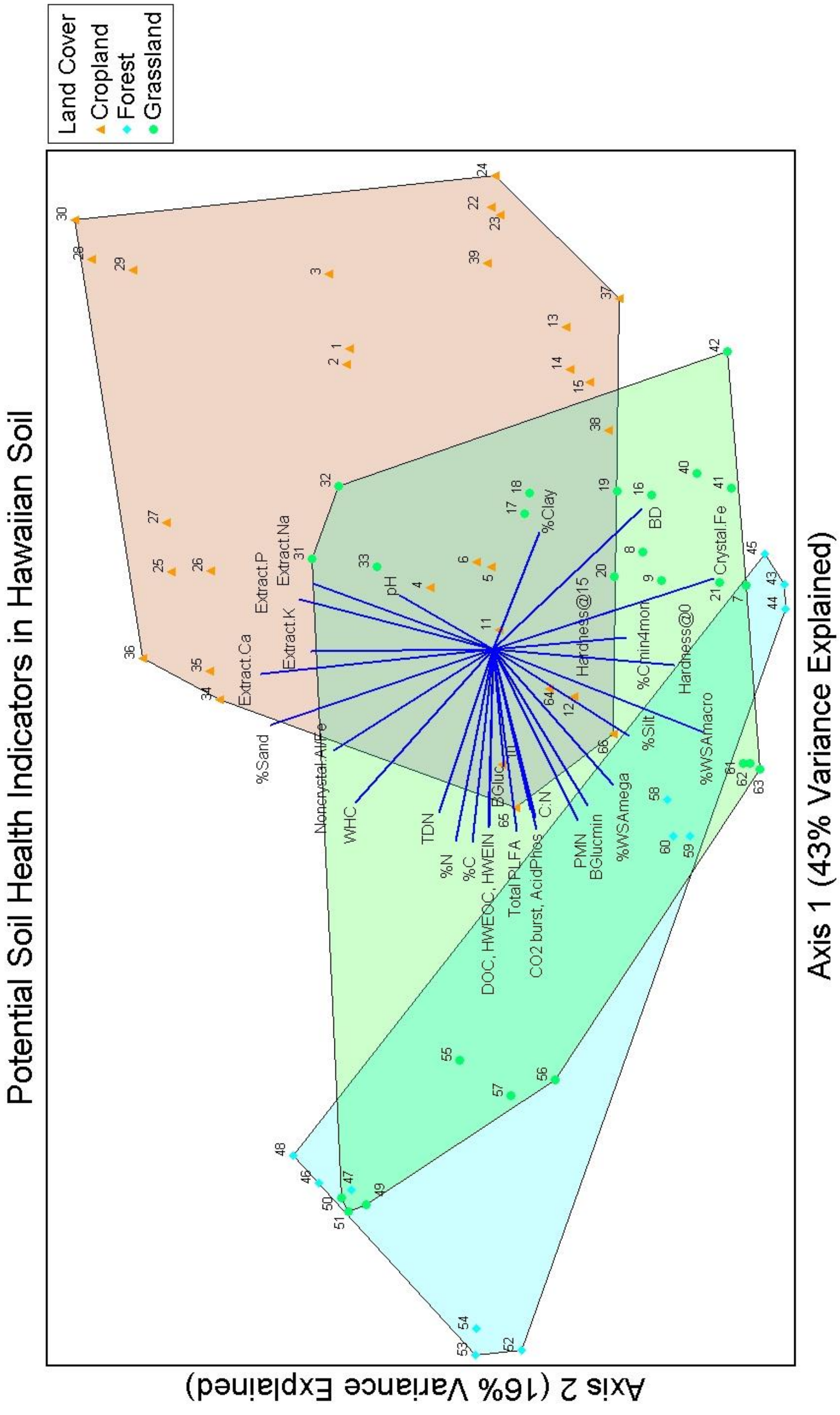


Figure 2.7 PCA ordination of all plots and potential soil health indicators with the overlay of land cover to group plots by color.

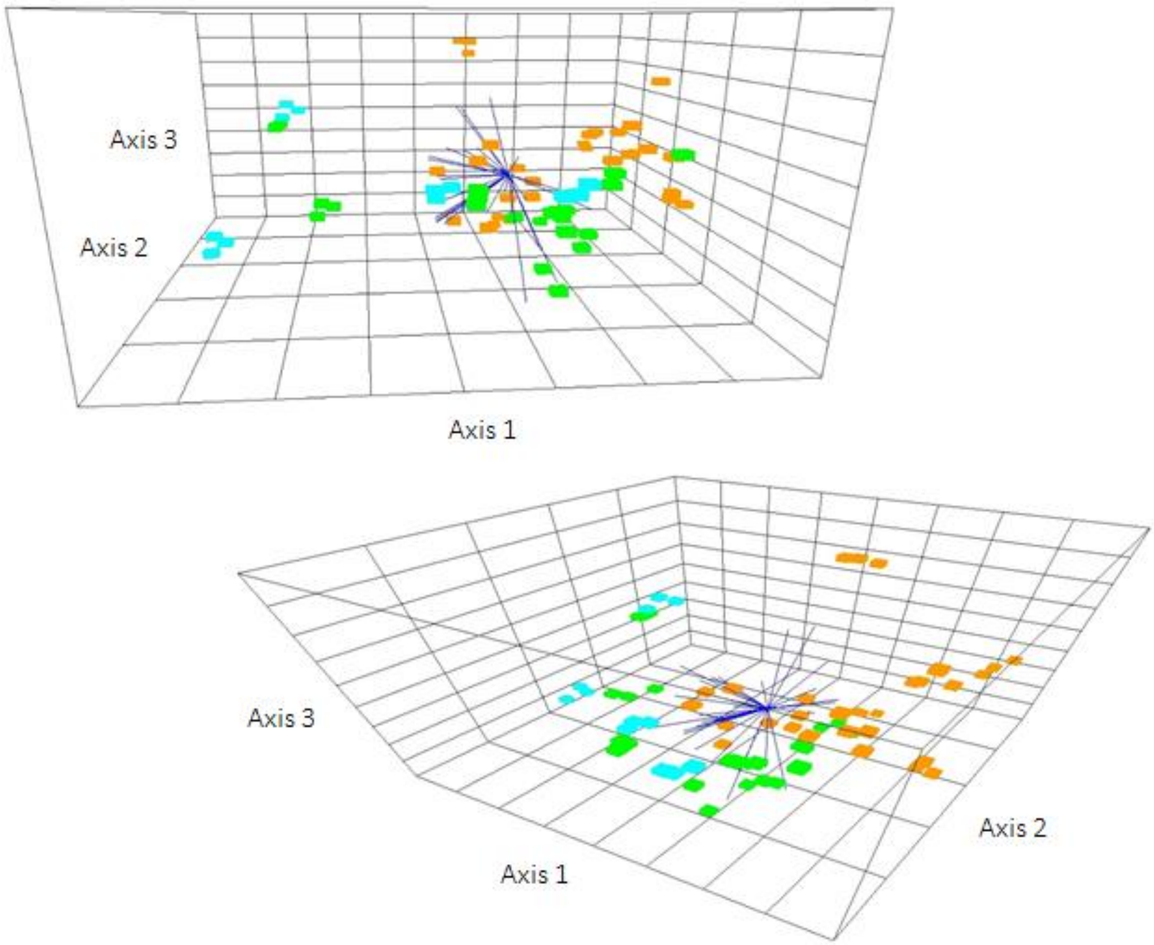
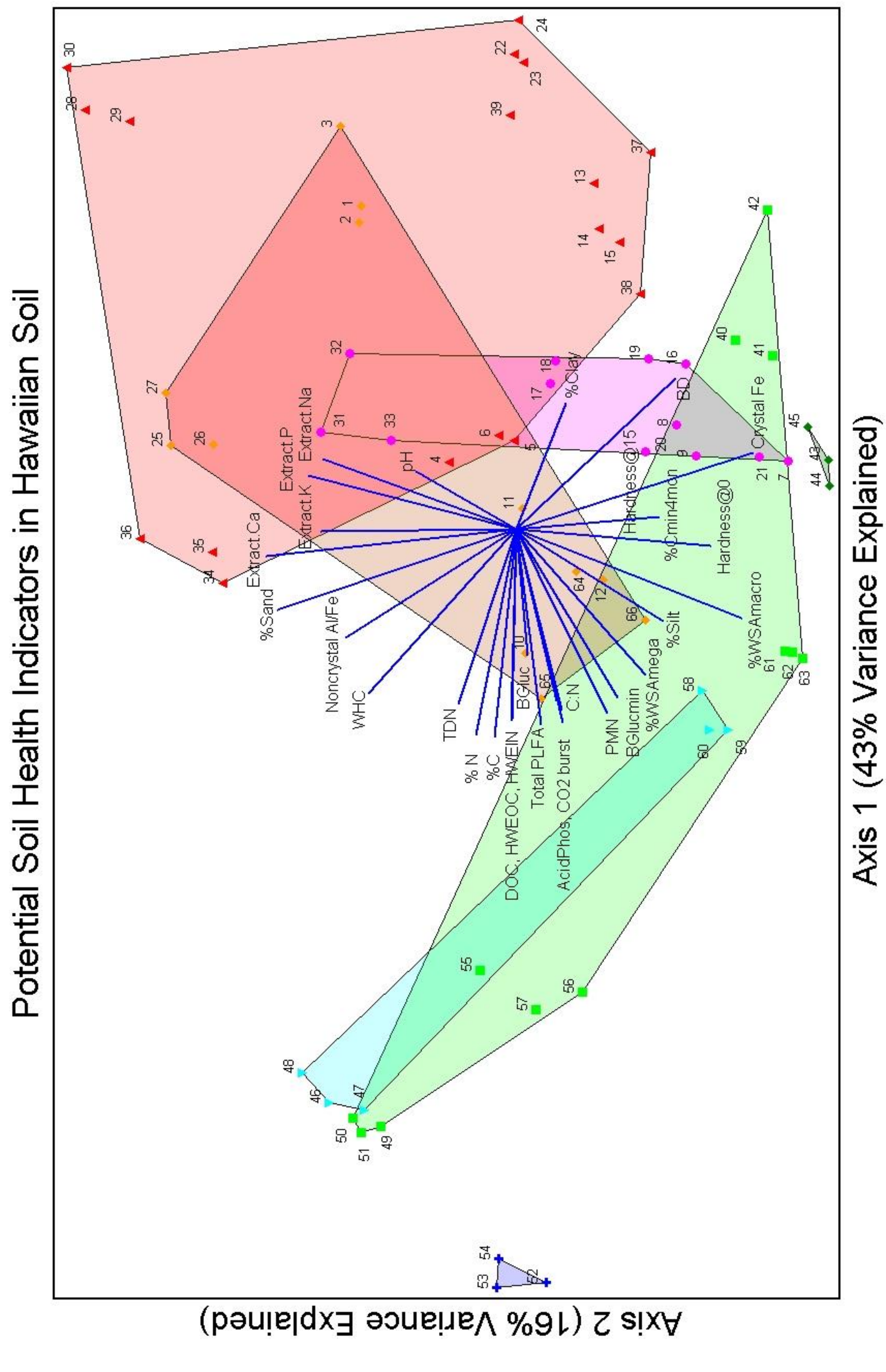


Figure 2.8 3D graphs of PCA with the overlay of land cover, sites of the same land cover (by color) generally cluster together, however, there is still considerable overlap in the groups suggesting that land cover does not sufficiently describe shifts in second matrix groupings.

PCA with management

Within the hierarchy of site grouping under land cover, six additional management options equate to a total of seven groups based on land cover and management and again visually show shifts in management happening primarily along Axis 1 (Figure 2.9). In 3D space, the overlap of sites is clearly reduced for group clusters (Figure 2.10). Plots in the pristine native forest (52-54) and other forest sites were associated in the direction with higher values of total percent organic carbon, as well as various indicators of soil life, while the sites under current conventional agriculture appear on the opposite end of Axis 1 with lower carbon and soil life. The overlay of management helps in understanding differences within forest and cropland sites, but there is still a large amount of unexplained variability within pasture and each cropland group (Figure 2.9). Because management alone does not explain all site differences, other environmental overlays are examined to understand some overlapping areas.



Potential Soil Health Indicators in Hawaiian Soil
Axis 1 (43% Variance Explained)
Axis 2 (16% Variance Explained)
Extract.Ca
Extract.K
Extract.P
Extract.Na
pH
%Sand
Noncrystal Al/Fe
WHC
TDN
% N
%C
DOC, HWEOC, HWEIN
BGluc
Total PLFA
AcidPhos, CO2 burst
C:N
PMN
BGlucmin
%WSAmega
%Silt
%WSAmacro
Hardness@0
%Cmin4mon
Hardness@15
BD
Crystal Fe
%Clay

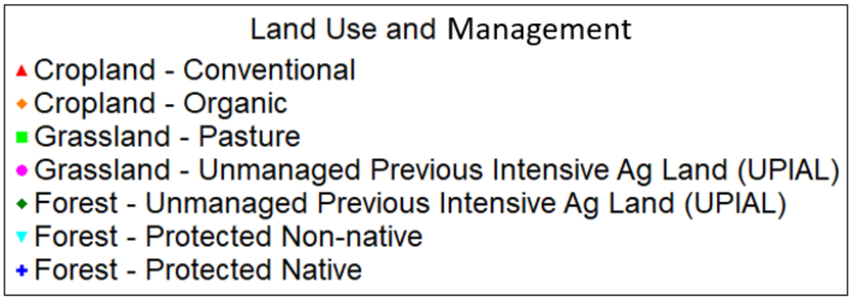


Figure 2.9 PCA ordination of all plots and potential soil health indicators with the overlay of land cover and management to group plots by color.

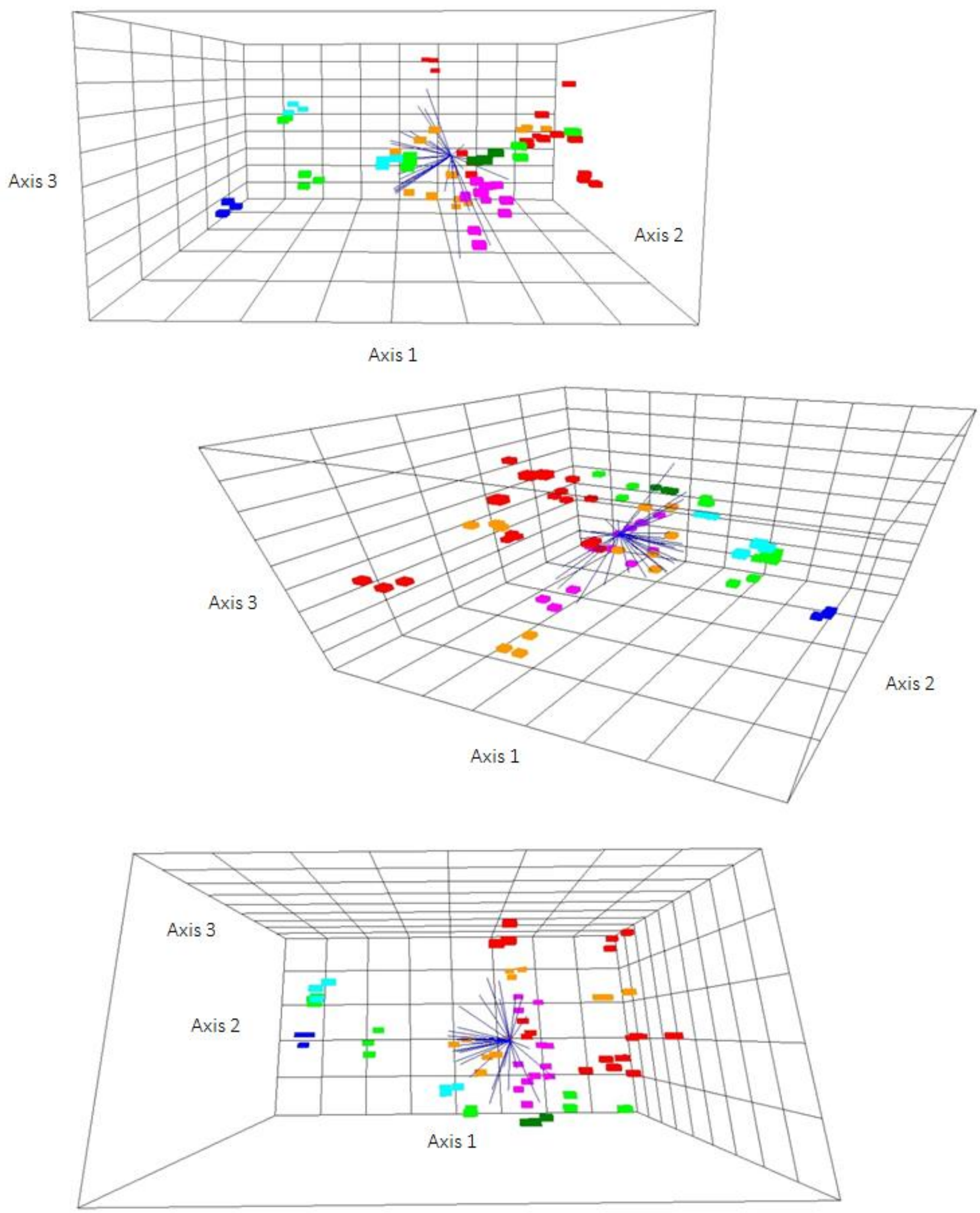


Figure 2.10 3D graphs of PCA with the overlay of land management and the site groups demonstrating clearer delineation of spatial similarity than using land cover alone.

PCA with soil disturbance

The intensity of soil disturbance ranging from low to very high provides information to the spatial segregation of some groups with high variability. In the pasture group, the land disturbance second matrix overlay now breaks those sites into regions of low and high disturbance (Figure 2.11). Due to standard practices of cropland agriculture, all sites under cropland land cover demonstrate very high soil disturbance and so the overlay offers little extra information as to the reason for high variability within those organic and conventional sites.

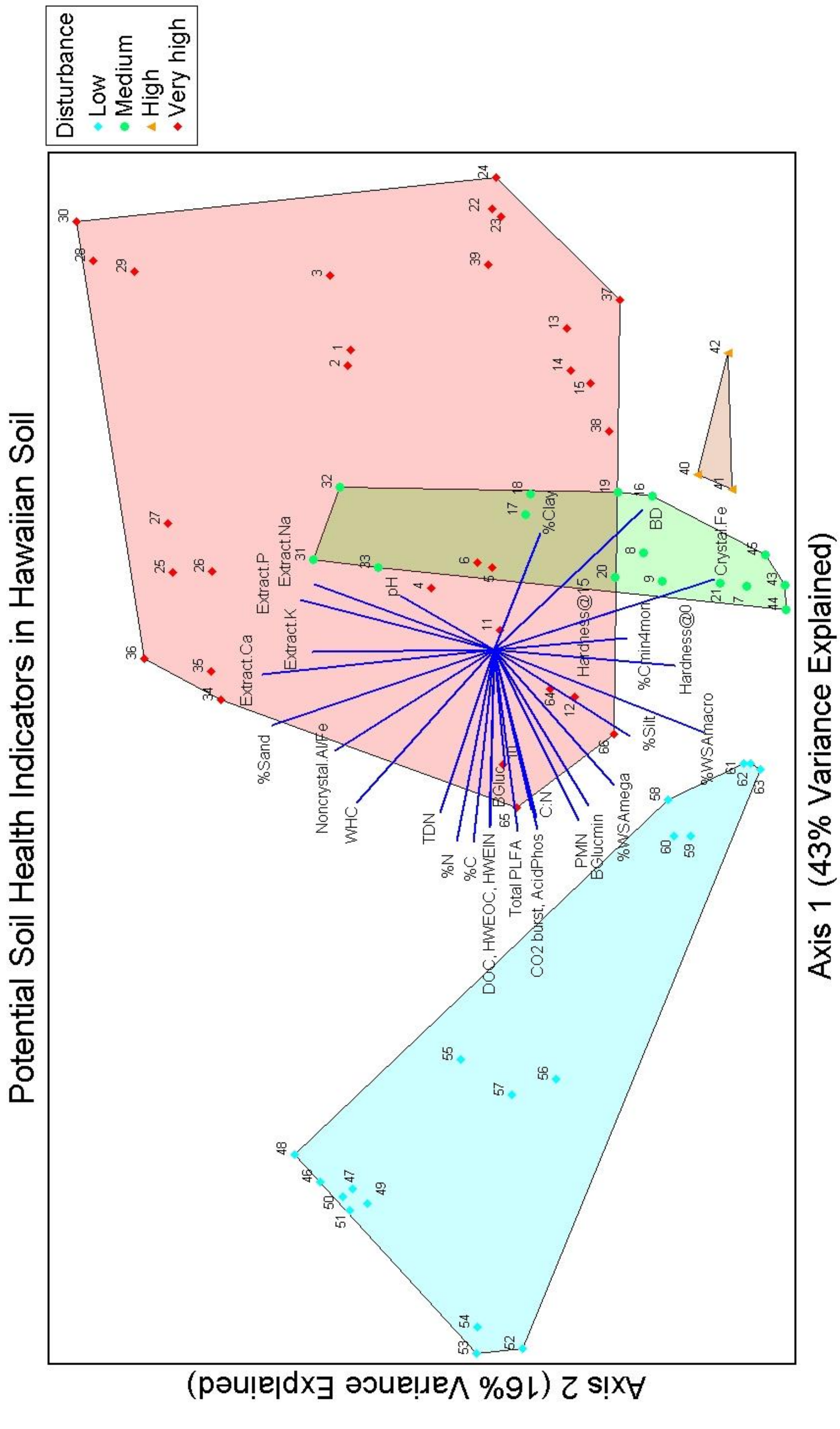


Figure 2.11 PCA ordination of all plots and potential soil health indicators with the overlay of intensity of soil disturbance to group plots by color.

PCA with soil order and series

In the final overlay option for second matrix data, taxonomy clearly shows distinct impact upon the site distributions as well. On the level of soil order, groups of sites of the same order cluster into similar spatial regions, demonstrating the importance and impact upon values of measurable indicators related to soil health and independent of management (Figure 2.12). However, unlike the previous overlays, the shifts between orders appear to generally happen along Axis 2 and less so along the dominate Axis 1. Some of the high variability observed within the Inceptisols, which span nearly the entire Axis 1, can likely be attributed to differences in soil series (Figure 2.13). Site R (plots 52-54, Inceptisol) of Amalu series is again isolated to the far left with Histic properties as well as management compared to other sites in the dataset.

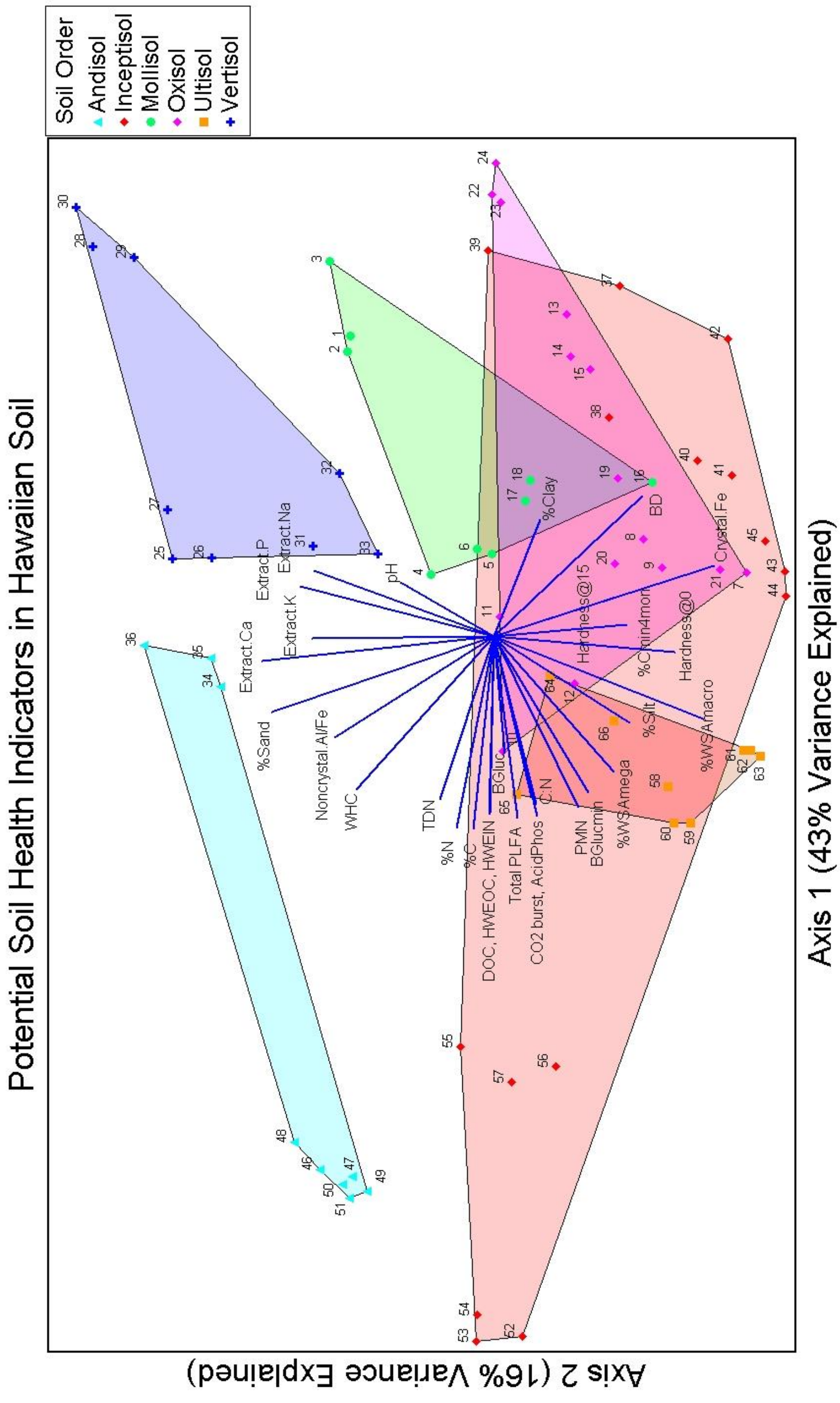


Figure 2.12 PCA ordination of all plots and potential soil health indicators with the overlay of soil order to group plots by color.

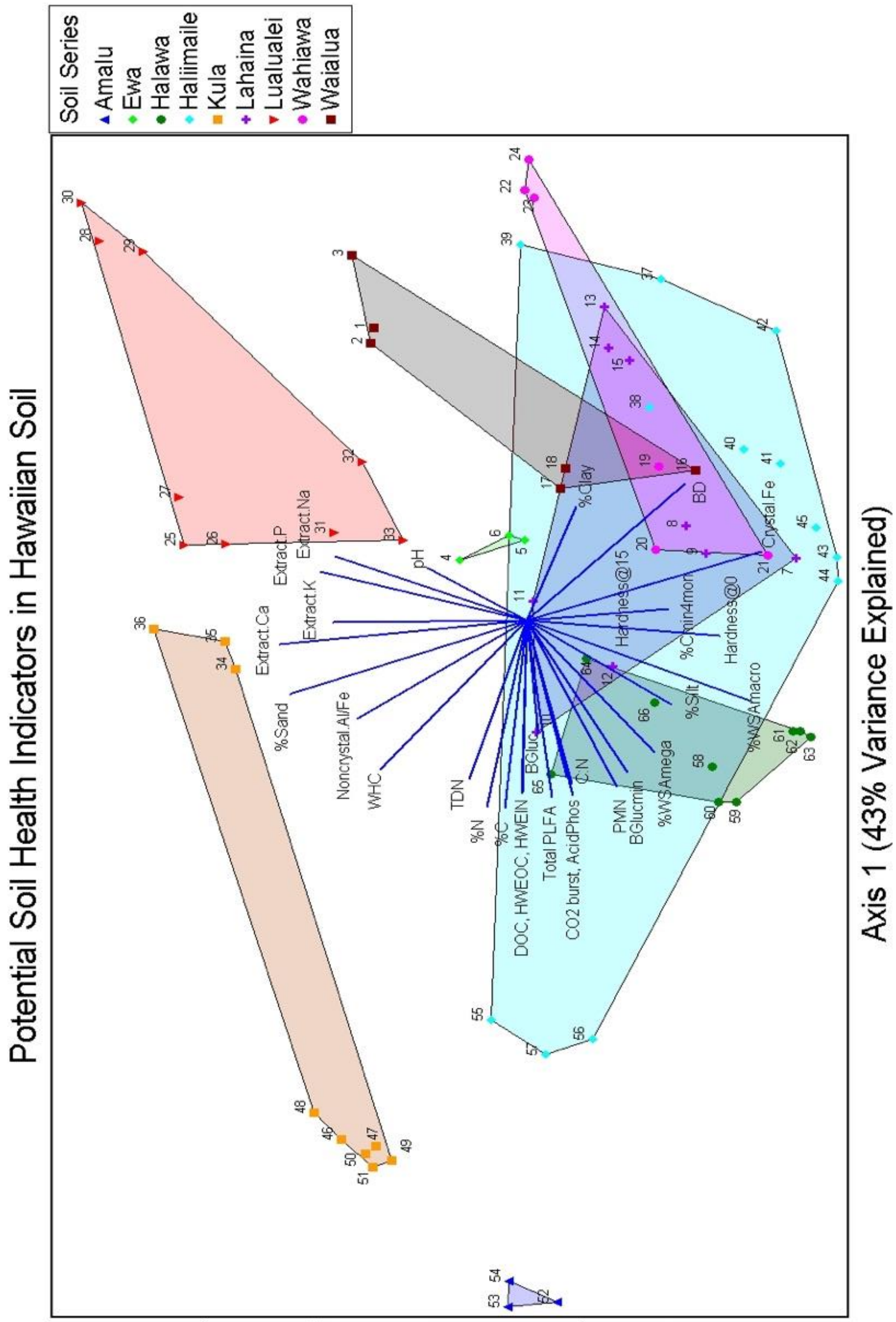
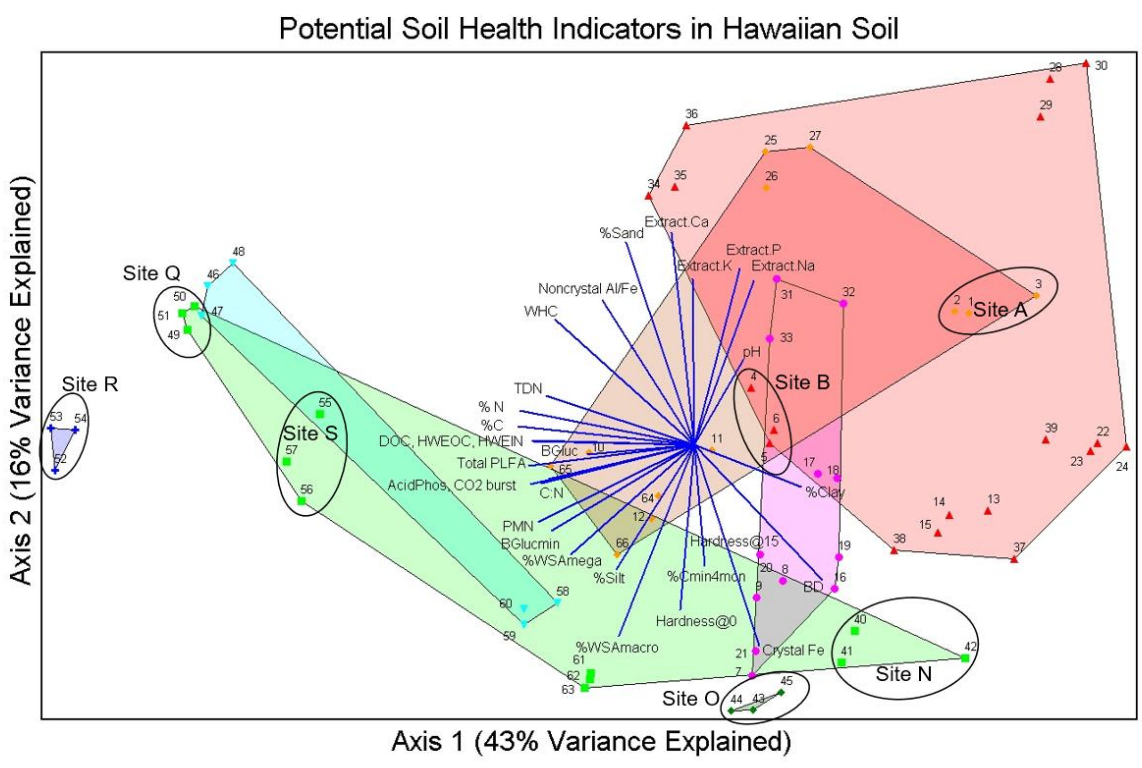


Figure 2.13 PCA ordination of all plots and potential soil health indicators with the overlay of soil series to group plots by color.

Importance of land use, history, management, and disturbance upon notable variability

While no one environmental variable perfectly explains all of the variability of sites, management appears to best identify clusters of meaningful differences with the clearest association to major data variance (Axis 1). The overarching differences between soils were also explained and meaningfully clustered to some degree by land cover, disturbance, and taxonomy. However, some subtle discrepancies remained within the identified management groups which stood out in the PCA, and site-specific descriptions of which provide a greater understanding of plot distribution to help identify patterns related to soil health (Figure 2.14).



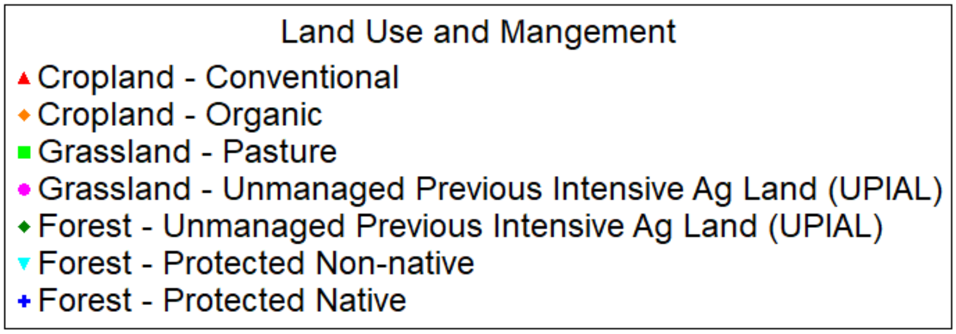


Figure 2.14 The PCA ordination of sample plots grouped by land management across all land uses, and identification of sites with notable descriptions.

Grassland

Within the grassland sites, the "pasture" group is notably very large, spanning widely along Axis 1 (Figure 2.14). Of the grassland sites under UPIAL, most variability vertically can likely be attributed to differences in soil order (plots 31-33) (Figure 2.12). On the far right, plots 40-42 (Site N) show a closer association towards the conventional cropland. Site N, now managed as quality pasture was disc-tilled within the last four years and had been under intensive long-term sugar cane agriculture prior which lead to reduced soil organic matter and negative impacts on soil physical and biological properties (Beare et al., 1994). While its history deems it to be a previous agriculture land, its current management qualifies it as pasture. In contrast, plots 49-51 (Site Q) on the far left of the pasture group exhibit opposite characteristics. This site has had little to no disturbance over the last two centuries, as a high quality pasture land, yet is also a Andisol which likely explains much of the apparent differences. The value of disturbance data is best demonstrated, however, by isolating the spatial distance between Site N and pasture plots 55-57 (Site S) which fall within the same soil series (Haliimaile). Site S has had minimal disturbance and has been managed for high quality pasture grass for nearly a century. While it is under the same current management and soil series as Site N, it's intensive agriculture history potentially contributed to it being spatially closer to conventional agriculture sites than near the undisturbed grasslands

<u>*Forest*</u>

The forest sites showed general closeness spatially to each other, apart from one site, and they trended with higher organic matter and soil life as expected based on land cover alone (Figure 2.14). Plots 52-54 (Site R) are by far the most unique group of samples in this dataset. Existing in wet conditions with poor drainage and high accumulated carbon, this site is nearly a Histosol. This Histic Inceptisol is also of pristine native forest condition and exhibits notably high values in nearly all biological and carbon-related parameters. As a result, plots within Site R are isolated on the far left (Figure 2.14). Because of its unique history, vegetation, and management, it required its own category of management. In the opposite direction, plots 43-45 (Site O) fall into another unique category of land use. Site O is notably far from other forest groups, which can likely be attributed to its pedogenic origin (Inceptisol) as well as historical data of being under intensive agriculture 40-50 years prior and its current vegetation characterized by invasive species. Such supplemental information for Site O could explain why it is spatially plotted closer to the other UPIAL sites rather than forest groups, regardless of its land cover being different from other UPIAL sites (grasslands).

<u>*Cropland*</u>

Overall, the respective effects of cropland land use (distinguished as either organic or conventional) on soil properties appeared to behave as expected, exhibiting lower values overall in carbon and soil life and particularly lower in the conventional group (Figure 2.14). However, two Mollisol sites differing in management and soil series, plots 1-3 (Site A) and 4-6 (Site B), behaved opposite from expected (Figure 2.13). Site A is currently managed organically, yet was under conventional agriculture just five years prior, while Site B has been under conventional agriculture long term. Crops at Site A were recently sprouted during the time of soil collection and soil was recently tilled prior to sample collection in contrast to Site B. Site B, while conventional, was at the end of harvest and likely had not been treated for pesticides (or tillage) in a more considerable amount of time than Site A. It is unknown how the inherent differences in soil series impact the differences observed in these two sites. All site differences considered, this highlights the challenge of providing one fully-descriptive label per site.

2.4.4 Land cover, management, and disturbance drive soil differences

Soil data variance and major axis associations

The visual assistance of PCA allows for the explanatory data groups and their patterns with the data variance to be more easily identified. Recalling that the greatest soil variance observed was on significant Axis 1, shifts in explanatory data groups were observed primarily horizontally along Axis 1, particularly land use, management, and soil disturbance. Shifts of taxonomy groups generally occurred in a vertical fashion along Axis 2. Land management appeared to show the strongest horizontal trend as supported with identifying group centroids, or spatial centroids, on the PCA (Figure 2.15). However, it is important to consider that centroids are impacted by all points within the group and unusual or notable plots such as the cropland Mollisols (1-6) and historical disturbance differences of the pasture sites cannot be adjusted without removing plots all together. Nonetheless, the overlay of management shows a strong visual relationship with the greatest data variance and suggests that it is the lead driver of differences in indicators related to soil health.

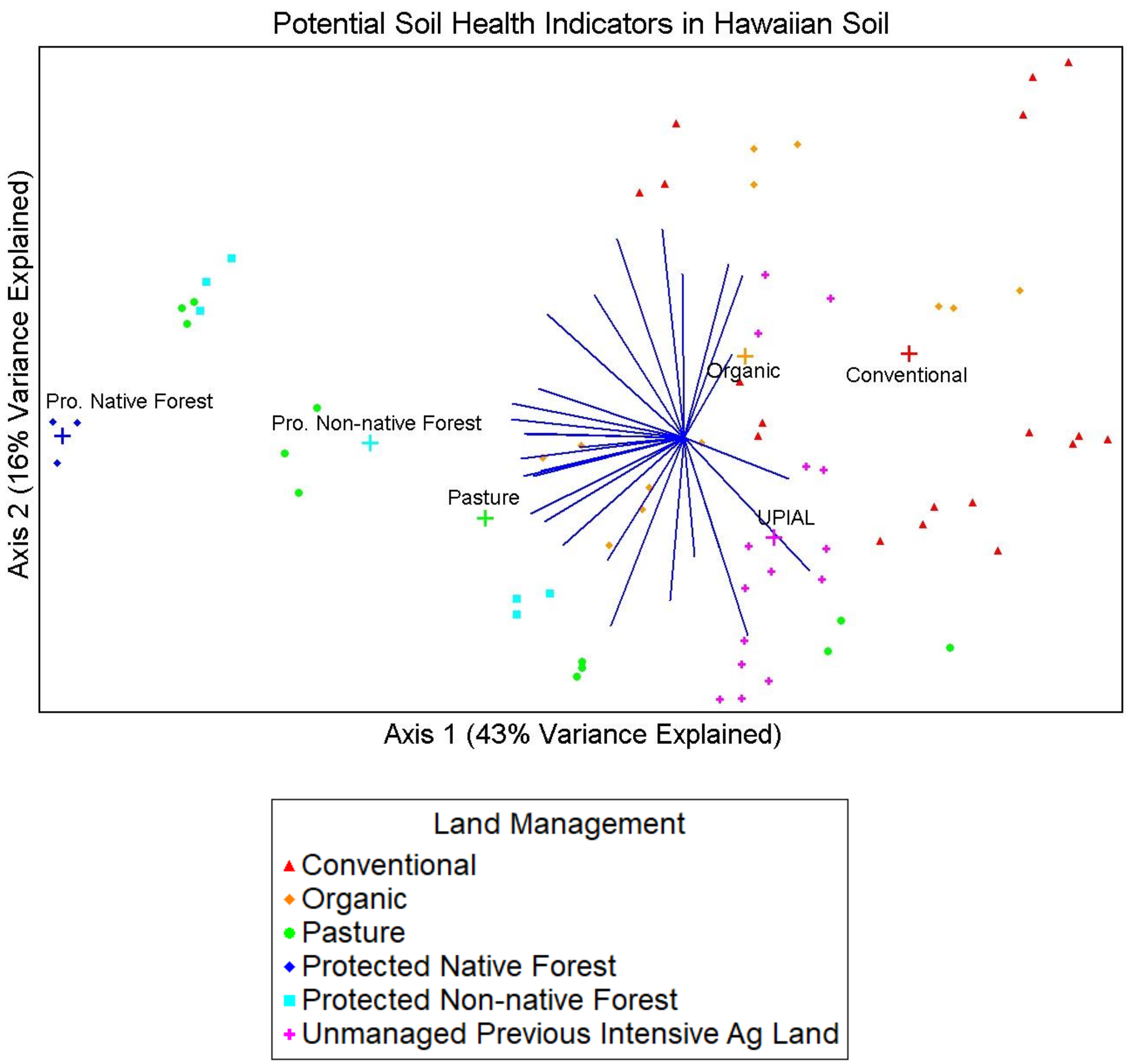


Figure 2.15 The PCA ordination of sample plots with group centroids, using the overlay of management across all sites.

Gradient of management related to soil health

The experimental design of data collected intended to capture high soil diversity across a wide range of soil health potential, and the highest variance between sites showed the strongest association to land management groups. While soil health cannot yet be defined as a response variable to the management groups without a developed index, optimal values for indicators selected to represent soil health increased the left of Axis 1 (2.6). This trend across many variables supports the observation that a spectrum of soil health may be observed along Axis 1 with greater soil health towards to the left. Variables most strongly correlated to the spectrum of data variance on Axis 1 are soil carbon and indicators measuring soil life, with increasing amounts of each to the left (negative correlation to Axis 1). Following in support of a potential soil health gradient along Axis 1, higher values of biological activity and carbon content are typically associated with greater soil health as they represent the living ecosystem in the soil as well as the necessary substrate for life (Moebius-Clune et al., 2016). For those indicators loading primarily on Axis 1 in contrast to Axis 2, the negative correlation of nearly all "more is better" indicators of soil health associate with the less disturbed land cover and management groups on the left (pasture and forest) displaying higher values of these parameters (Figure 2.6, Figure 2.9). This observation of the site grouping associations to soil health indicators is supported in studies of landscapes with low disturbance, where soil aggregation is higher along with greater soil life, as well as plant residue accumulation on the surface showing reduced loss of soil organic matter and resulting in increased soil carbon (Havlin et al., 1990). Higher organic carbon content and soil microbial biomass also have been shown to consistently represent higher soil health using various methods of soil quality assessment in a meta-analysis from Karlen et al. (2001). The observed gradient of differences in soil characteristics relating to soil health suggests that protected forests are on the optimal end of land use and management to achieve high soil health regarding a soil ecosystem with optimized soil functions, and conventional cropland on the less-optimal end (Figure 2.16). Such findings of minimally disturbed areas with high values for "more is better" indicators of soil health, and more disturbed areas having lower values for "more is better" indicators of soil health, supports reasoning to use Axis 1 as an exploratory method of identifying sensitive indicators of soil health. Hypothesis one, stating that the intensity of agricultural activity is a main driver of differences in indicators representing measurements related to soil health is accepted.

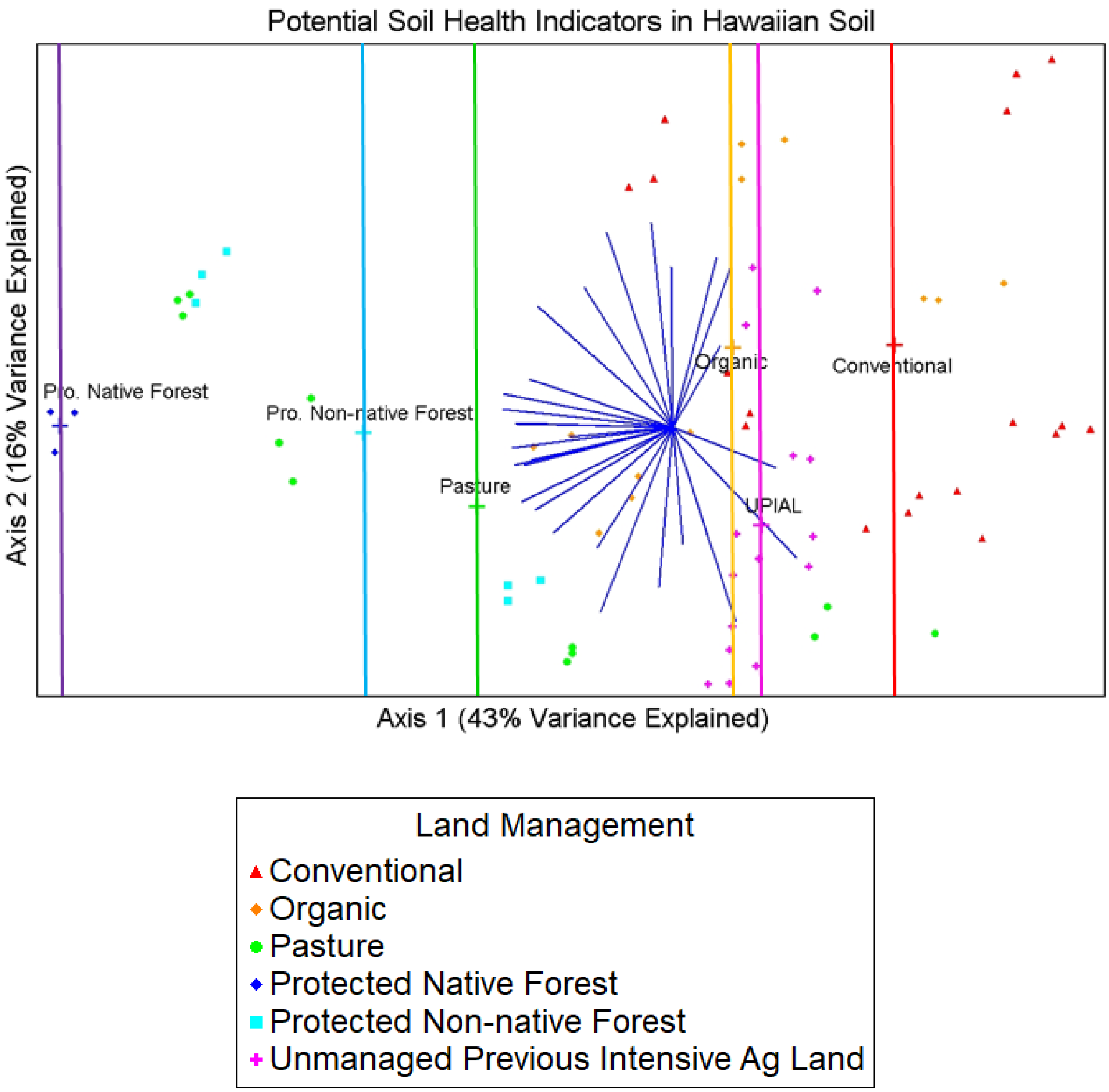


Figure 2.16 The PCA ordination of sample plots with group centroids demonstrating the horizontal shift of groups marked with a corresponding colored vertical line, using the overlay of land management across all land uses.

A nonparametric procedure for testing differences in data groups (multiple response permutation program, MRPP) was used to find significant differences between the identified management groups appearing along the gradient of potential soil health (Table 2.8). MRPP was selected because of the compatibility with non-distributional assumptions (McCune and Grace, 2002). Significant differences were observed between all groups along the gradient (Figure 2.16, 2.17). However, because the MRPP group differences are measured in multiple dimension space rather than a linear line as proposed for the gradient, this method should be considered as supplemental support for the observed soil health gradient but not serving as a definitive statistical analysis.

Table 2.8 Results of a multiple-response permutation program (in PC-ORD) to test significance of multidimensional spatial differences between the proposed varying management groups.

Multiple-response permutation program (MRPP)

Group identifiers	p-value
Conventional vs. UPIAL	0.00119
UPIAL vs. Organic	0.0000181
Organic vs. Pasture	0.000483
Pasture vs. Protected Forest	0.0545

Connections between land use and "soil health" as a relative term

The exploratory nature of these results demonstrate how known attributes of soil health can be applied to management and land use in Hawai‘i. "Soil health" as a relative term can mean many things to different land users, however, patterns of soil qualities associated with the selected definition of soil health and critical soil functions are observed to trend along the high variability identified in the PCA. "The continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans," (NRCS, 2018) applies to the selected landscapes with various critical soil functions which translate into goals for the soil (e.g., to protect native vegetation, to raise animals, to grow vegetables) and with a wide range of ecosystem diversity. From this definition we can reinforce that healthy soil is about soil as a living entity. The physical and chemical indicators of soil health represent the processes that support life such as soil structure and soil nutrients. The biological biomass and microbial processes that cycle nutrients and interact with physical and chemical properties of soil create a living ecosystem, which, sustains plants, animals, and humans. Hence, the balance of physical, chemical, and biological indicators all play vital roles in maintaining soil life and hence soil health, and all are impacted by disturbance to the soil. Visual interpretation of the PCA helped to identify a gradient of land disturbance with management, and the data suggests that a Hawai‘i gradient of soil health by management is seen from left to right on Axis 1 representing optimal to less optimal soil health, respectively (Figure 2.17).

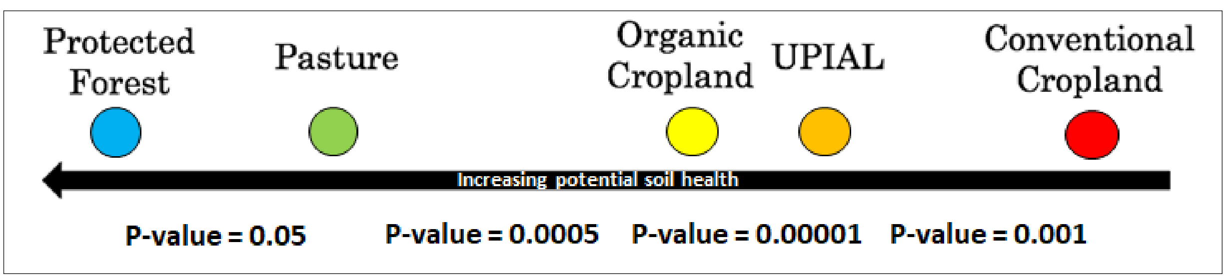


Figure 2.17 PCA group centroids from management displayed a gradient of Hawai‘i potential soil health increasing to the left, and suggest land management as a strong driver of differences in potential soil health (p-values between groups derived from MRPP analysis, Table 2.8 [Note: MRPP values measure multidimensional space differences and are only used as supplemental data to the proposed linear gradient]).

There is room for improvement at any point on the soil health continuum, with a measured shift in health to the left seen as a positive management practice. Those practices that facilitate shifts to the left, while supporting the livelihoods of land managers, exhibit the benefits of having a soil health index. Identifying those practices that can reliably assist in shifts are necessary to associate soil health with the benefits to farmers. While there are limitations to the relevance of this gradient for practical reasons such as modern humans requiring agricultural land for food, the identification of such a gradient can hone goal setting for restoration of degraded lands, give farmers tangible guidelines for improving soil, and be useful to track soil health over time.

2.4.5 A reduced set of sensitive indicators for development of a soil health index

Sensitive indicators and correlations to major data variance

Indicators were reduced by quantitative and qualitative criteria beginning with the quantitative reductions. The greatest explanatory factor of differences in potential soil health in reviewing PCA trends was seen along Axis 1, and associated to land management (Figure 2.16, Figure 2.17). Therefore, those variables with strong correlations to Axis 1 were identified to be the most sensitive indicators of differences across the diversity of soils and potentially most useful as indicators of soil health (Karlen et al., 2001). Due to the exploratory nature of PCA as a method of statistical analysis, there is no standard of what correlation values are deemed appropriate and potentially significant. Generally, statistical correlations (absolute value) equal to or less than 0.35 represent low or weak correlations, 0.36 to 0.67 are moderate correlations, 0.68 to 0.90 are strong, and above 0.90 are very strong (Taylor, 1990). Those parameters equal to or above 0.68 correlation to Axis 1 were considered statistically strong and potentially sensitive.

From 30 potential indicators of soil health, 15 showed a correlation greater than 0.68 and were considered strong enough to be retained for further evaluation (Table 2.9).

Table 2.9 Correlation values of indicators to all four significant PCA axes organized in order of strength to the dominant axis, with those parameters above 68% correlation are considered strong and potentially sensitive (*).

Increasing absolute correlation to Axis 1

Variables related to soil health, all land management	Correlation coefficient to significant axis (% Variance Explained)			
	Axis 1 (42.6%)	Axis 2 (15.7%)	Axis 3 (9.1%)	Axis 4 (7.2%)
% Total organic C	-0.98 *	0.06	0.11	0.05
% Total N	-0.97 *	0.11	0.08	0.08
Total PLFA	-0.92 *	-0.07	-0.26	-0.05
24 hr CO_2 burst	-0.91 *	-0.13	-0.26	0.02
Dissolved organic C	-0.90 *	0.01	-0.31	0.10
Hot water extractable C	-0.89 *	0.01	-0.32	0.10
Potentially mineralizable N	-0.89 *	-0.26	-0.23	0.01
Acid phosphatase	-0.85 *	-0.13	-0.13	-0.01
Hot water extractable inorganic N	-0.84 *	0.01	-0.03	0.09
Total dissolved N	-0.82 *	0.17	-0.24	0.18
C:N	-0.81 *	-0.12	0.21	-0.08
Beta-glucosaminidase	-0.79 *	-0.29	-0.16	-0.38
Water holding capacity	-0.77 *	0.42	-0.12	0.29
Bulk density	0.71 *	-0.46	-0.09	-0.32
% Water-stable mega-aggregates	-0.69*	-0.37	0.25	-0.34
Beta-glucosidase	-0.59	-0.03	-0.18	-0.59
% Clay	0.59	-0.14	-0.70 *	0.11
Non-crystalline Fe/Al	-0.51	0.49	0.38	-0.09
% Silt	-0.43	-0.42	0.56	0.09
% Water-stable macro-aggregates	-0.42	-0.64	0.22	-0.36
% Sand	-0.38	0.68 *	0.34	-0.27
Crystal-bound Fe	0.36	-0.68 *	0.07	-0.20
Extractable Na	0.33	0.55	-0.23	-0.08
pH	0.27	0.29	0.05	-0.70 *
Extractable P	0.25	0.59	-0.30	0.14
Hardness at 15 cm	0.20	-0.37	-0.35	-0.29
Extractable Ca	-0.12	0.71 *	0.02	-0.45
Hardness at 0 cm	-0.08	-0.56	0.01	0.35
% C mineralized, 4 mo. incubation	0.06	-0.41	-0.70 *	-0.16
Extractable K	-0.01	0.56	-0.45	-0.29

Further consideration of cropland sensitivity

The soil health index is critical for cropland systems as a tool to assist farmers in implementing soil management strategies that aggrade soil health and function. To ensure that cropland sensitivity is captured, results of an additional PCA were considered. The experimental design combined diversity of management within soil taxonomy, yet not necessarily the same combinations. This was an inevitable product of landscape and soil order interactions (e.g., inherently fertile soil types for croplands), as well as what is finitely available for sampling. Because the strength of variables correlating to main axes changed considerably when looking only at the cropland and UPIAL sites during PCA data balance assessment, the indicators sensitive to change within a second analysis were compared to the results of the full landscape. The cropland system PCA determined three significant axes, cumulatively explaining 65% of the overall data variance (Table 2.10). The major Axis 1 explained 29% variance, Axis 2 with 22%, and Axis 3 with 14% (Table 2.11). No patterns of useful second matrix association were observed from Axis 3 so it was not graphically displayed.

Table 2.10 Randomization results from the PCA output are used to determine the number of significant axes for interpretation, with the first three axes considered significant (p-value < 0.05).

RANDOMIZATION RESULTS
999 = N = number of randomizations

Axis	Eigenvalue from real data	Eigenvalues from randomizations: Minimum	Average	Maximum	p *	n
1	8.7427	2.4253	2.9399	3.6496	0.001000	0
2	6.4885	2.2194	2.6063	3.1346	0.001000	0
3	4.2367	2.0601	2.3706	2.7338	0.001000	0
4	2.1729	1.9178	2.1680	2.4599	0.467000	466
5	1.4518	1.7356	1.9896	2.2504	1.000000	999
6	1.1928	1.5839	1.8279	2.0684	1.000000	999
7	1.1306	1.4025	1.6816	1.8721	1.000000	999
8	0.92700	1.3483	1.5486	1.7782	1.000000	999
9	0.74707	1.1885	1.4267	1.6379	1.000000	999
10	0.66532	1.1303	1.3075	1.4926	1.000000	999

Table 2.11 Variance extracted results report the percent of variance explained per axis as well as cumulatively. A cumulative total of 64.9% data variance is explained from the three significant axes (Table 2.10).

VARIANCE EXTRACTED, FIRST 10 AXES

AXIS	Eigenvalue	% of Variance	Cum.% of Var.	Broken-stick Eigenvalue
1	8.743	29.142	29.142	3.995
2	6.489	21.628	50.771	2.995
3	4.237	14.122	64.893	2.495
4	2.173	7.243	72.136	2.162
5	1.452	4.839	76.975	1.912
6	1.193	3.976	80.951	1.712
7	1.131	3.769	84.720	1.545
8	0.927	3.090	87.810	1.402
9	0.747	2.490	90.301	1.277
10	0.665	2.218	92.518	1.166

The cropland PCA showed two axes of similar strength pulling management groups in opposite directions. Again, the dominant axis associated best with management practice (Figure 2.18), however, with a strong impact of soil order as well from Axis 2 (Figure 2.19). Due to recent disturbance across all cropland samples, the level of historical disturbance was not a useful predictor of potential indicator differences. Similar to the full landscape PCA, 'more is better' indicators strongly associated with soil carbon and soil biology showed to increase towards the left of the graph where the organic management group exists (Figure 2.18). Towards the right are the conventional agriculture sites and the UPIAL sites generally observed in between organic and conventional on Axis 1. The only overlap observed between groups are due to Mollisol plots 1-6 (Site A and B) which, as previously mentioned, behaved against expectations.

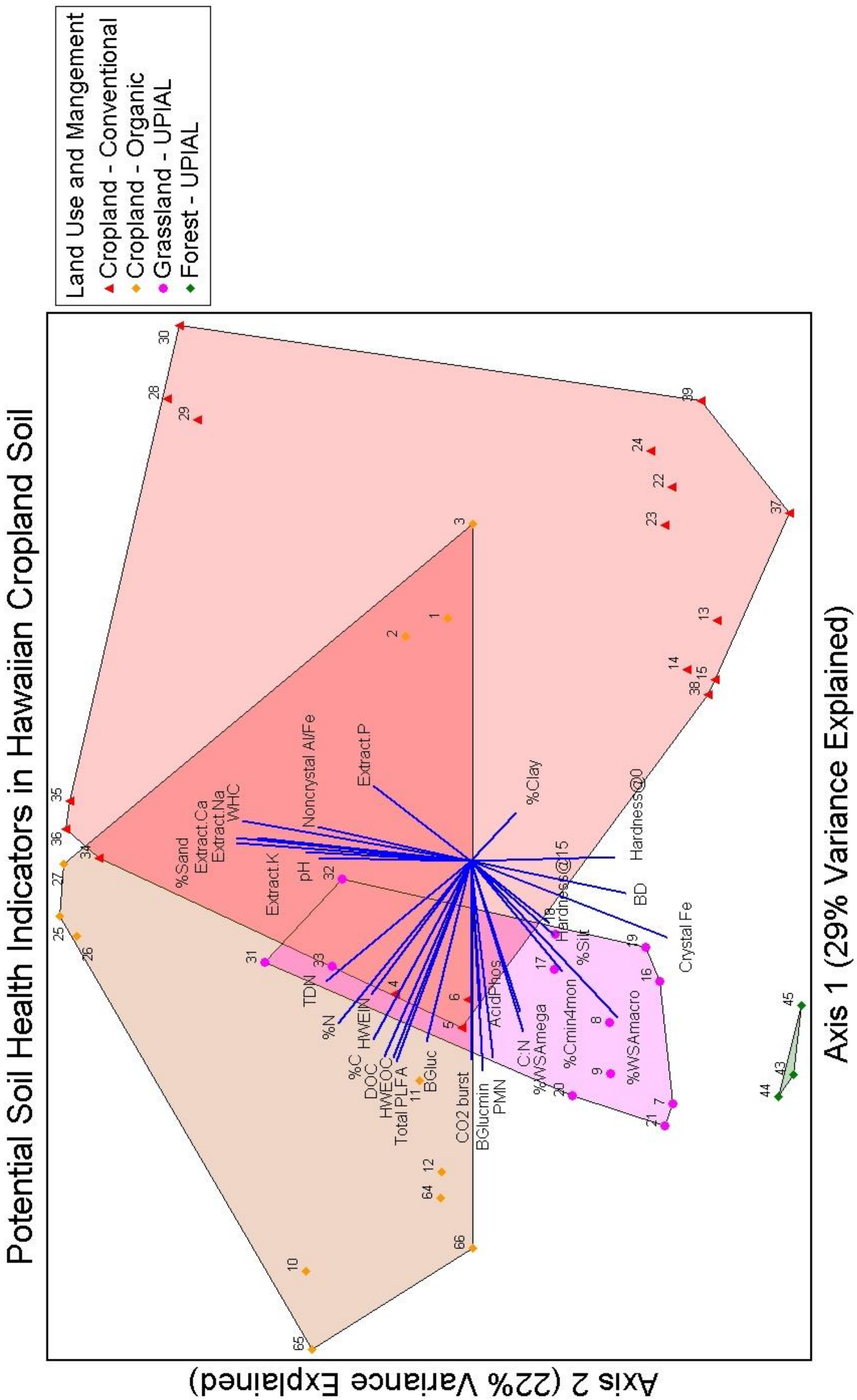


Figure 2.18 The PCA ordination of cropland and UPIAL plots and all potential soil health indicators with the overlay of land use and management.

While Axis 1 shows variation associated with management, Axis 2 has a clear association with inherent soil properties relating to soil taxonomy (Figure 2.19, Figure 2.18). Soil order generally shifts vertically with Axis 2 showing that soil taxonomy must be considered when interpreting cropland soil health indicator values. Because Axis 1 again appears to dominate the variability of data as it relates to potential changes in soil health and management represents dynamic qualities that can be changed, indicator correlations to Axis 1 are evaluated for their sensitivity and potential to be used in a soil health index.

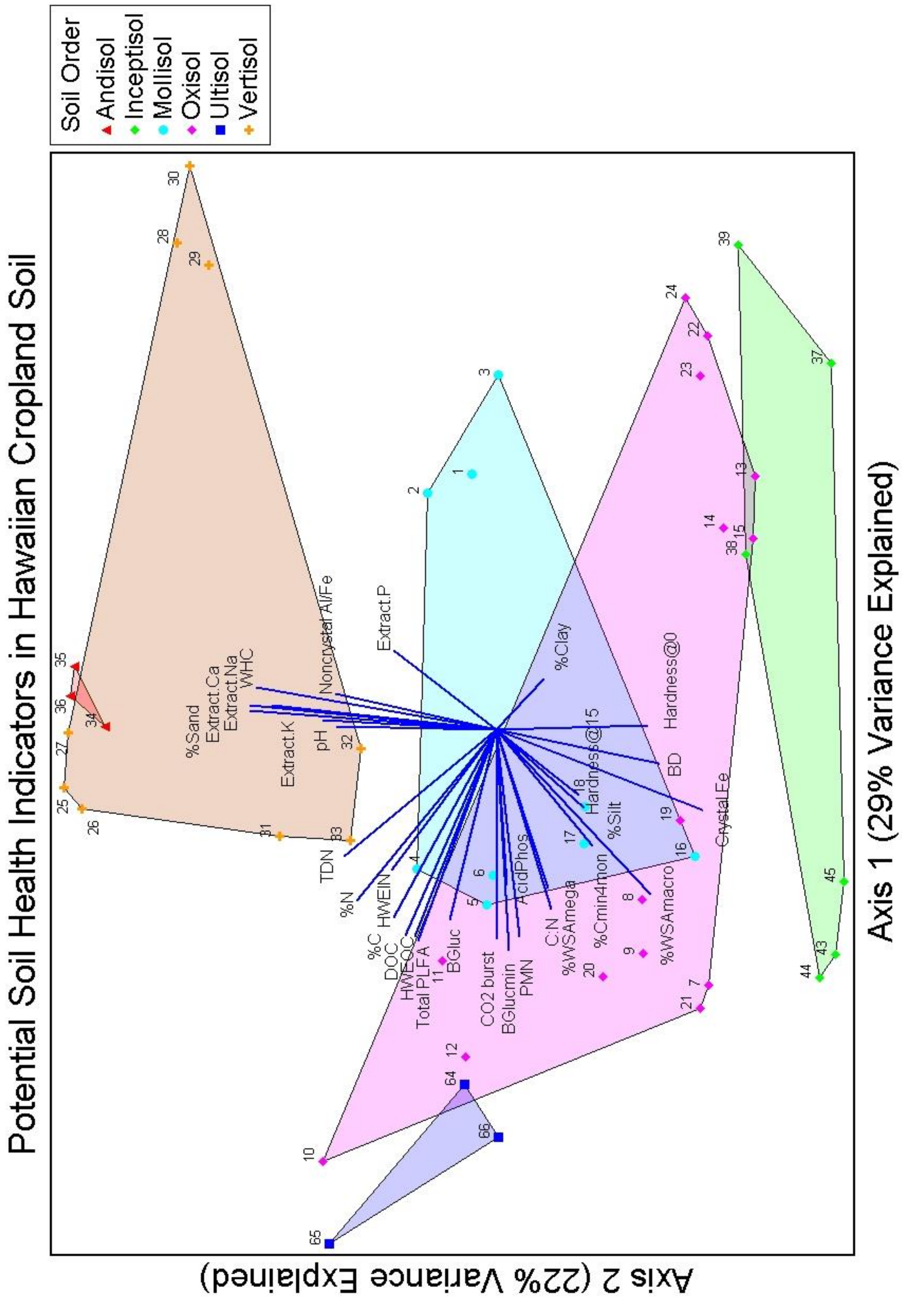


Figure 2.19 The PCA ordination of cropland and UPIAL plots and all potential soil health indicators with the overlay of soil order.

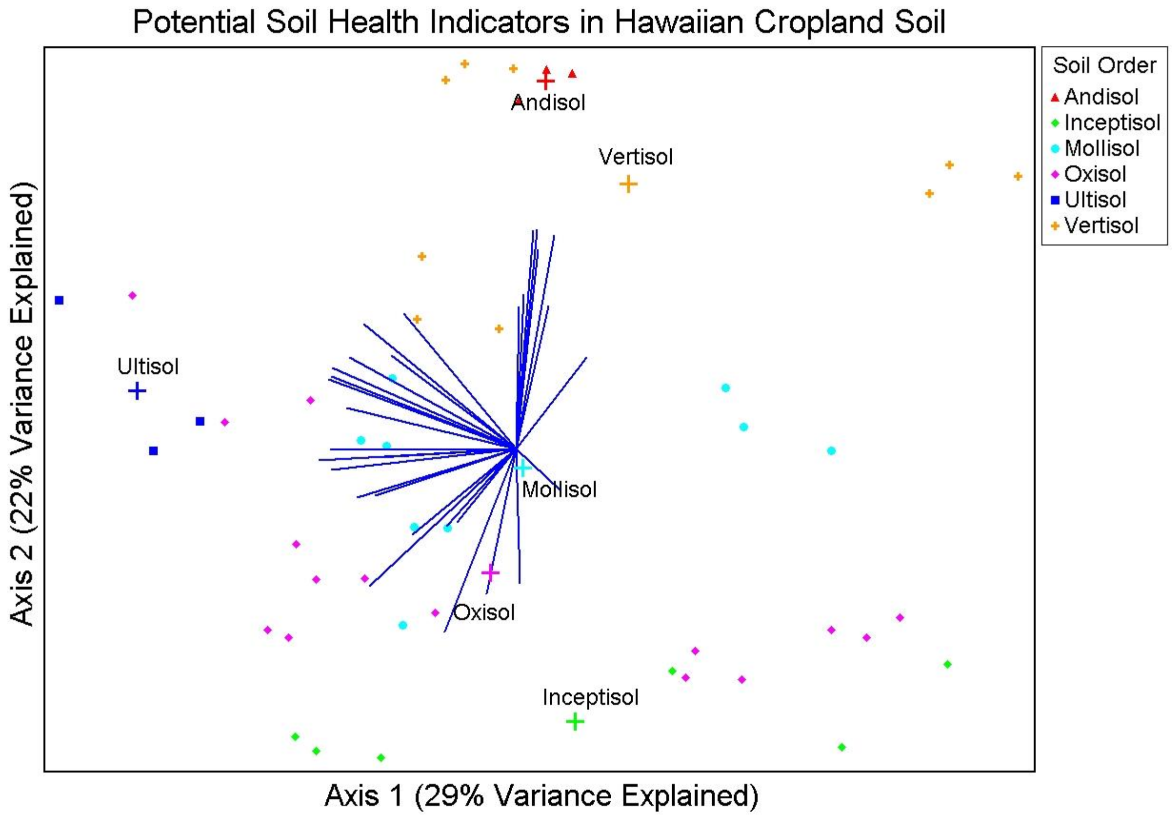


Figure 2.20 The PCA ordination of cropland and UPIAL plots with group centroids, using the overlay of soil order. Centroids of the groups generally show shifts in taxonomy occurring vertically along Axis 2, rather than associating with the dominant axis of data variance explained.

The PCA output of indicator correlations to significant axes identifies similar sensitive indicators to those from the full landscape PCA. The only sensitive soil health indicator in croplands with a 68% or greater correlation value to Axis 1 that was not included in the full landscape analysis was β-glucosidase, and a near-qualifying value for water-stable macro-aggregates (Table 2.12). To maintain the applicability of soil health testing to be representative of cropland needs, β-glucosidase was added to the final list of sensitive indicators. While the water-stable macro-aggregate indicator did not have a strong correlation, it is recommended as a potential indicator to consider for cropland-specific testing as it with a near-strong correlation value of 0.65 (Table 2.12).

Table 2.12 Correlation values of indicators to all three significant PCA axes from cropland and UPIAL soils organized in order of strength to the dominant axis, and those parameters above 68% correlation are considered strong and potentially sensitive (*).

Increasing absolute correlation to Axis 1

Variables related to soil health, cropland management	Correlation coefficient to significant axis (% Variance Explained)		
	Axis 1 (29.1%)	Axis 2 (21.6%)	Axis 3 (14.1%)
Beta-glucosaminidase	-0.88 *	-0.04	-0.24
Total PLFA	-0.84 *	0.27	-0.29
24 hr CO_2 burst	-0.83 *	-0.01	-0.28
Potentially mineralizable N	-0.82 *	-0.08	-0.16
Hot water extractable C	-0.82 *	0.28	-0.28
Dissolved organic C	-0.82 *	0.31	-0.28
Beta-glucosidase	-0.75 *	0.16	-0.22
% Total organic C	-0.75 *	0.35	0.50
% Water-stable mega-aggregates	-0.71 *	-0.19	0.36
% Total N	-0.68 *	0.48	0.45
% Water-stable macro-aggregates	-0.65	-0.53	0.21
C:N	-0.63	-0.18	0.40
Acid phosphatase	-0.62	-0.03	0.00
Hot water extractable inorganic N	-0.56	0.36	0.26
Total dissolved N	-0.50	0.52	-0.09
% C mineralized, 4 mo. incubation	-0.46	-0.33	-0.65
Crystal-bound Fe	-0.32	-0.70 *	-0.01
Extractable P	0.32	0.35	-0.36
% Silt	-0.31	-0.30	0.68 *
Hardness at 15 cm	-0.26	-0.28	-0.32
% Clay	0.20	-0.16	-0.88 *
Water holding capacity	0.17	0.82 *	-0.16
Non-crystalline Fe/Al	0.14	0.55	0.60
Bulk density	-0.13	-0.56	-0.43
Extractable Na	0.10	0.77 *	-0.14
Extractable Ca	0.10	0.84 *	-0.25
% Sand	0.08	0.84 *	0.31
Extractable K	0.04	0.59	-0.43
Hardness at 0 cm	0.02	-0.52	0.01
pH	0.01	0.54	-.033

Multicollinearity, soil function, and practicality of sensitive indicators

The sensitive indicators selected through PCA were examined comparatively for multicollinearity, to further downsize recommended indicators. The PCA process resulted in a reduction to sixteen indicators including: % total organic carbon, % total nitrogen, PLFA, 24-hour CO_2 burst, dissolved organic carbon, hot water extractable organic carbon, potentially mineralizable nitrogen, acid phosphatase, hot water extractable inorganic nitrogen, total dissolved nitrogen, C:N, β-glucosiminidase, water holding capacity, bulk density, water-stable mega-aggregates, and β-glucosidase. This group of 16 indicators cover all five critical soil functions and represent a balance across biological, chemical, and physical soil measurements (Table 1.1) (Karlen et al., 2001). Using a correlation matrix between untransformed parameters, highly sensitive indicators with R^2 values above |0.90| were considered very strong and suitable for further reduction (All indicators in Figure 2.21, sensitive indicators in Figure 2.22) (Taylor, 1990, Karlen et al., 2001). Hot water extractable inorganic nitrogen, total dissolved nitrogen, dissolved organic carbon, acid phosphatase, and total nitrogen were removed, as all showed high correlation to other sensitive indicators with overlap in their intended measured soil function as well as lesser practicality in contrast to their comparable indicators (Table 2.13).

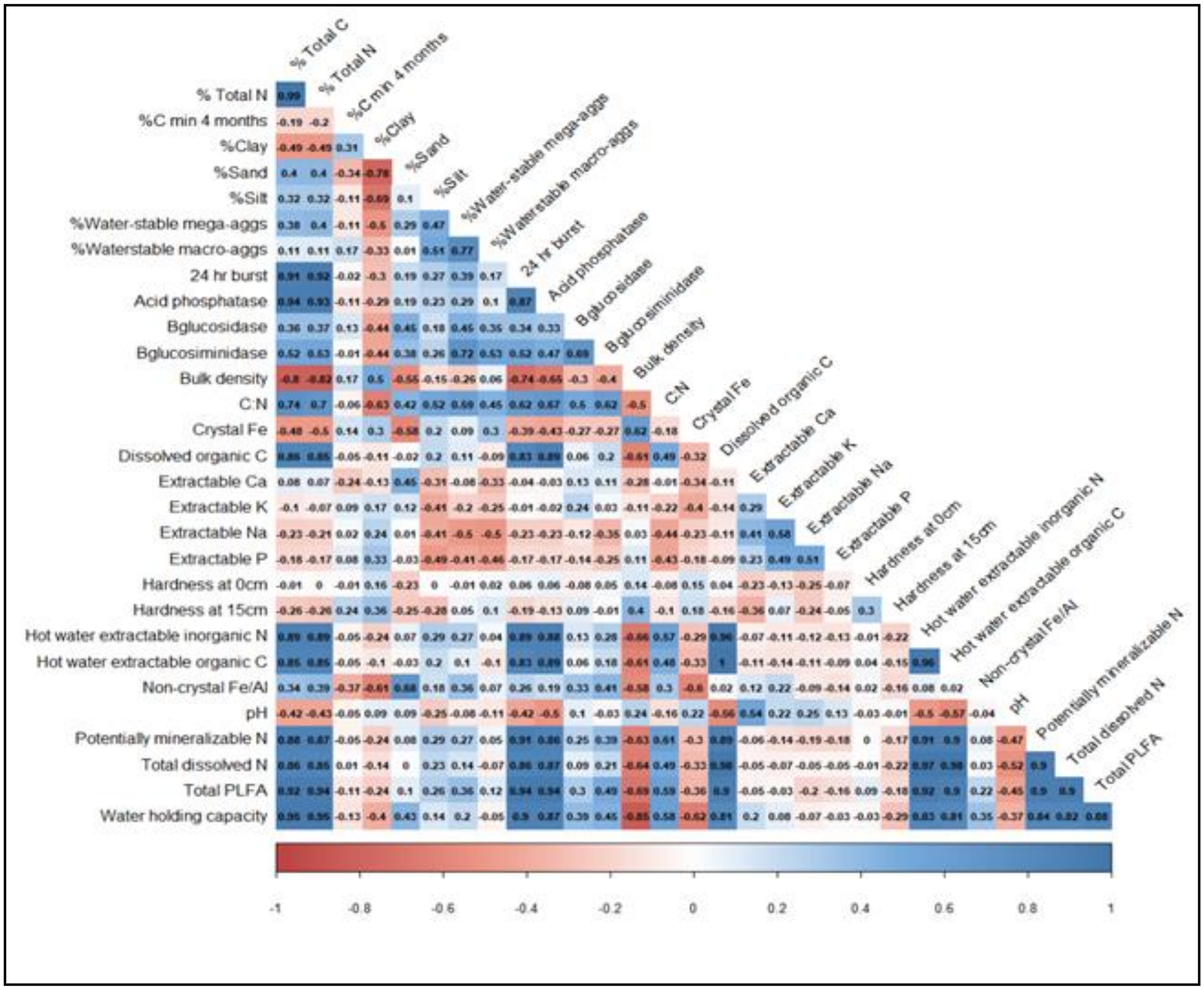


Figure 2.21 A correlation matrix between all untransformed parameters, values range from -1 to 1 and also indicated by color. Values greater than |0.90| are considered very strong.

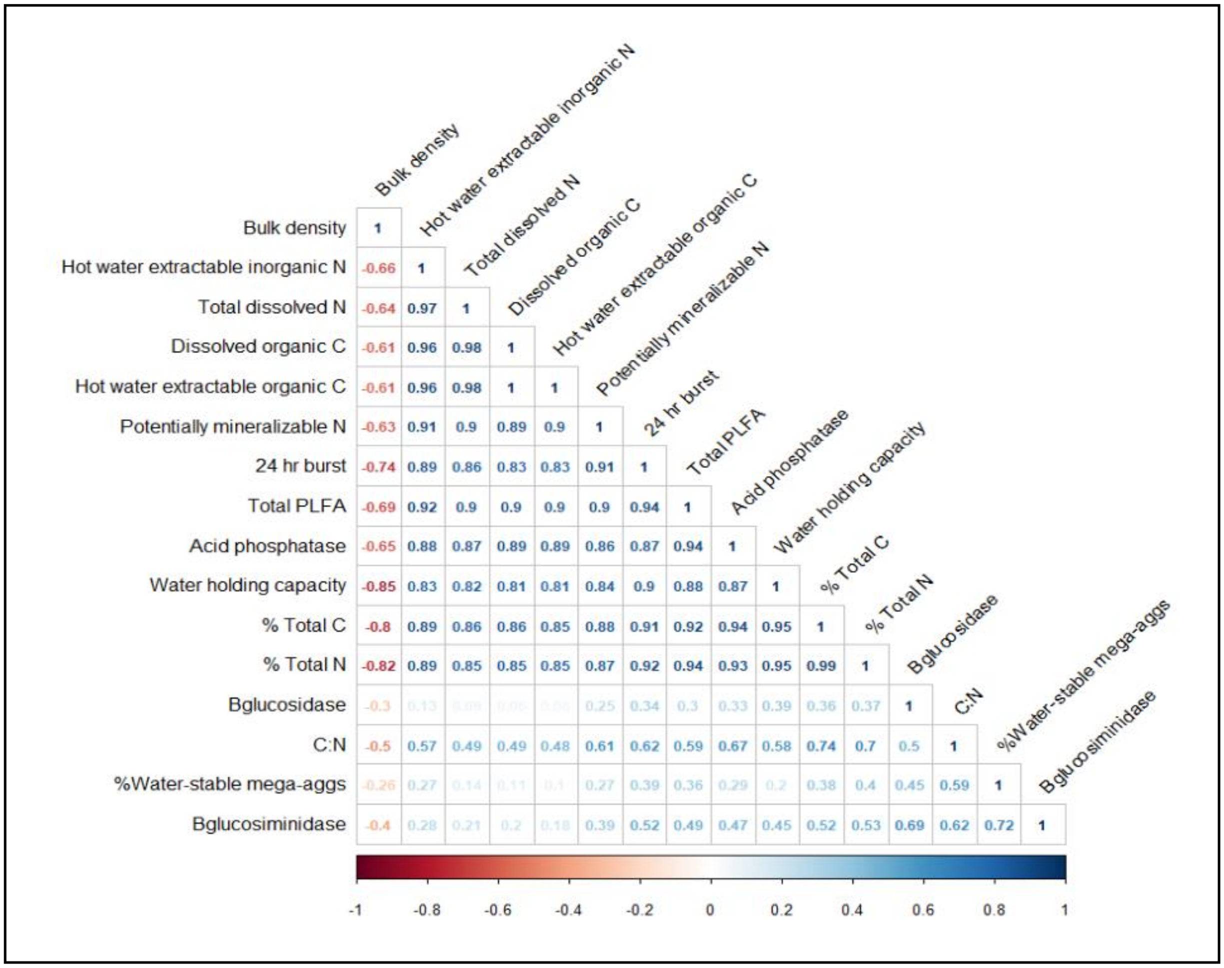


Figure 2.22 A correlation matrix between the 16 untransformed parameters considered to be sensitive along from PCA, that could be further reduced by logic of multicollinearity. Values range from -1 to 1 and are also indicated by color. In this figure, high values are clustered to clearly see those that can be considered for reduction.

The final step in the indicator reduction process involved a qualitative assessment of the practicality and cost of the measurement. Indicators that required extensive or experienced labor or incurred high costs were candidates for removal. With those limitations, bulk density was removed due to the difficulty of acquiring an undisturbed core in the field, and PLFA was removed due to high cost and the need for outsourced testing, which required extensive soil handling and preparation. Indicators excluded by all processes of reduction are summarized in Table 2.13.

Table 2.13 A list of 21 indicators excluded from recommendations for routine Hawai‘i soil health testing.

Indicator Removed	Reasoning for Removal
% Sand	No strong correlation to a dominant PCA axis (<0.68), indicator that is more sensitive to inherent soil properties than dynamic properties
% Silt	No strong correlation to a dominant PCA axis (<0.68), indicator that is more sensitive to inherent soil properties than dynamic properties
% Clay	No strong correlation to a dominant PCA axis (<0.68), indicator that is more sensitive to inherent soil properties than dynamic properties
Extractable Calcium	No strong correlation to a dominant PCA axis (<0.68)
Extractable Sodium	No strong correlation to a dominant PCA axis (<0.68)
Extractable Potassium	No strong correlation to a dominant PCA axis (<0.68)
Extractable Phosphorus	No strong correlation to a dominant PCA axis (<0.68)
% Total C Mineralized (4 month incubation)	No strong correlation to a dominant PCA axis (<0.68)
Hardness at 0cm	No strong correlation to a dominant PCA axis (<0.68)
Hardness at 15cm	No strong correlation to a dominant PCA axis (<0.68)
% Water-stable macroaggregates	No strong correlation to dominant PCA axis (<0.68), could be included to supplement cropland-only testing
pH	No strong correlation to a dominant PCA axis (<0.68)
Total PLFA	Expensive, temperature sensitive sample storage, requires outsourced analysis, highly covariate with CO_2 burst (R^2 = 0.94)
Bulk density	Professional skill required to obtain accurate sample
Crystalline Fe oxides	Strongly associated with soil order groups, requires outsourced analysis, no strong correlation to dominant PCA axis (<0.68)
Non-crystalline Fe/Al	Strongly associated with soil order groups, requires outsourced analysis, no strong correlation to dominant PCA axis (<0.68)
Total dissolved N	Highly covariate (R^2 = 0.90) and similar soil function to nitrogen measurement from mineralization (PMN)
Dissolved organic C	Highly covariate (R^2 = 0.99) and similar soil function to hot water extractable C
Hot water extractable inorganic N	Highly covariate (R^2 = 0.91, 0.96) to N mineralization (PMN) and hot water extractable C, similar soil function to PMN
% Total N	Highly covariate with % Total C (R^2 = 0.99) and similar soil function to N mineralization measurement (PMN) and C:N
Acid phosphatase	Expensive and tedious, highly covariate with hot water extractable C, N mineralization (PMN), and CO_2 burst (R^2=0.89, 0.86, 0.87), recommended to test if indication of P deficiency

The final set of sensitive and practical indicators

After assessing the sensitivity, interpretable value, feasibility, field collection practicality, and laboratory resources required, the best indicators to use in a routine soil health test for Hawaiʻi were reduced to nine parameters, capturing all five critical soil function goals (Table 2.14, Table 2.15). Hypothesis two, stating that values of water stable aggregates, potentially mineralizable nitrogen, soil respiration, and bulk density are the strongest indicators of soil health, is partially accepted. This partial acceptance acknowledges that while these variables are in the final index list, not all were the top sensitive variables and bulk density, despite its sensitivity, was excluded due to practicality.

Table 2.14 After assessing the sensitivity, interpretable value, feasibility, field collection practicality, and laboratory resources required, the recommended indicators to use in a routine soil health test for Hawaiʻi were reduced to 9 parameters.

Proposed Indicators of Hawaii Soil Health
Measured parameters of soil health span physical, chemical, and biological aspects of soil
Physical
Water Holding Capacity
Water-Stable Mega-Aggregates
Chemical
% Total Organic Carbon
C:N
Biological
24 hour CO_2 Burst
β-glucosidase
β-glucosiminidase
Hot Water Extractable Organic Carbon
Potentially Mineralizable Nitrogen

Table 2.15 The recommended nine indicators of Hawaiʻi soil health and their corresponding critical soil function.

	Recommended Indicator	Soil Function(s) Relation
Physical	Water holding capacity	Water supply, medium for plant growth, soil life
	% Water-stable mega-aggregates	Carbon storage and cycling, medium for plant growth, water infiltration and supply, soil life
Chemical	% Total organic C	Carbon storage, soil life
	C:N	Soil life, nutrient cycling
Biological	24 hr CO_2 burst	Soil life, nutrient cycling, carbon storage and cycling
	Hot water extractable organic C	Soil life, carbon storage and cycling
	Potentially mineralizable N	Soil life, nutrient cycling
	Beta-glucosiminidase	Soil life, nutrient cycling
	Beta-glucosidase	Soil life, nutrient cycling, carbon cycling

Biological indicators show highest sensitivity to soil variance

Biological indicators and those indicators closely reliant on biological processes showed the greatest sensitivity to data variability and hence soil management (Table 2.9). Meaningful measurements of soil health are intended to capture the changes in a soil ecosystem that are reflective of dynamic soil properties and are often most impacted by management (Karlen et al., 2008). While inherent soil qualities such as those most commonly found as chemical and physical indicators may take significant time to change in a soil or cannot change, dynamic qualities are a powerful tool in soil health assessment with indications of soil health changes that often precede detectable physical or chemical changes (Nielsen et al., 2002). The biological indicators as leading predictors of soil health can be attributed to their rapid responses to environmental stress associated with soil disturbance (Nielsen et al., 2002). Microbes play key roles in soil health such as decomposition of organic matter, mineralization of and recycling of nutrients, nitrogen fixation, detoxification of pollutants, maintenance of soil structure, biological suppression of plant pests, and the reduction of parasitism (Stirling, 2014, Brackin et al., 2017). The loss of such functions in the soil can be directly associated to loss of crop productivity (e.g., increases of plant pests leading to decreases in harvestable crop) and highlight the vital importance of soil life in hierarchical controls on critical soil functions.

Importance of physical and chemical indicators on soil health and fertility testing

While dynamic soil qualities are preferable to detect changes in soil health as they better relate to the soil ecosystem as a living entity, the impact of inherent soil qualities upon the soil ecosystem remain crucial (Karlen et al., 2008). Some of the physical and chemical potential soil health indicators, which did not show to be as sensitive as the biological measures, are considered dynamic and many of them are considered to be inherent qualities. Regardless of the group they fall into, physical and chemical soil qualities play crucial roles in soil function such as impacting the availability of nutrients and the structure of the soil which then holds water, air, and supports life. The sensitive indicators corresponding to Axis 2 of both PCAs (full landscape and cropland sensitivity) included nutrient measurements as well as those related to taxonomy (e.g., texture classes) (Table 2.9, Table 2.12). Particularly for cropland systems, these indicators greatly impact crop production and fundamental for proper soil nutrient management. In order to make appropriate fertilization choices in a commercial farming operation, soil fertility testing should be included in addition to a soil health test so as to not exclude crucial measurements regarding nutrients. Properly managed nutrients benefit both the farmer by achieving target yields and avoiding expensive and unnecessary nutrient additions as well as benefiting the environment by reducing risk of nutrient runoff, eutrophication, and pollution of nearby ecosystems.

2.4.6 Interpretation of soil health indicators

The values obtained from all potential indicators of soil health can vary in their interpretation whether it be "higher is better," "lower is better," or "optimal value." However, the reduced set of indicators are all generally considered to be of the "higher is better" category with the exception of C:N ratio which often falls into an "optimal value" category. The relationship of each to measured soil health can be supported from results of many other studies. Values vary with intrinsic soil differences, but the overall interpretation of indicator scores can be summarized in Table 2.16 along with potential supplemental fertility measurements.

Water holding capacity

A soil's ability to hold water is vital for sustained plant growth and supporting microbial life and is often correlated to the amount of organic matter in the soil as well as bulk density (Brady and Weil, 2008). During times of water shortage, be it between rainfall events or due to drought, water held in the soil allows plants and soil life to survive. Acting like a sponge, soils with the ability to hold high quantities of water increases soil ecosystem resiliency in the face of drought conditions. Thus, higher values of water holding capacity are ideal for a healthy soil ecosystem. In agricultural systems, high water holding capacity reduces the need for irrigation. Conventional practices of tillage and crop residue management are major contributors to the loss of water holding capacity, which is closely tied to the amount of soil organic matter and overall soil structure (Arais et al., 2005, Karlen et al., 2001, Evanylo and McGuinn, 2000).

Water-stable mega-aggregates

Soils with higher water-stable aggregates are associated with greater soil health as they improve the overall soil tilth by increasing water infiltration, water storage, water and gas exchange, total porosity, resistance to erosion, and by decreasing soil bulk density (Arai et al., 2014). Soil aggregates store organic C by physically protecting soil C from microbial decay as well as restrict the diffusion of oxygen and enzymes (Blankinship et al., 2016, Berhe et al., 2012). Agricultural practices such as tillage disrupt and reduce soil aggregates by physical destruction and lead to loss of soil structure which is vital to support life many soil functions such as carbon and water storage (Beare et al., 1994, Karlen et al., 2001, Haynes and Swift, 1990).

Percent total organic carbon

High organic carbon serves many vital soil ecosystem and productivity functions and correlates to important physical, chemical, and biological soil properties. It is additionally associated with soils more resilient to drought, extreme rainfall, and disease (Bot and Benites, 2005, Awale and Chatterjee, 2017). Intensive agriculture reduces soil organic matter content over time with many adverse effects (Arias et al., 2005).

C:N ratio

The C:N ratio compares the mass of carbon in the soil to the mass of total nitrogen and is an indicator of maintaining a healthy microbial environment, as microbes must obtain proper ratios of each to sustain their bodies (NRCS, 2019). Values for C:N ratios vary with vegetative cover and soil type and should be monitored to maintain a sufficient ratio for microbial function and to assess mineralization/immobilization dynamics (NRCS, 2019). In relation to soil health, it can be a useful predictor for disease suppression (van Bruggen and Semenov, 2000).

24 hour CO_2 burst

Soil respiration methods measure the metabolic activity of the microbial communities in the soil, an important aspect of soil fertility and a functional ecosystem (Haney et al., 2008). Greater respiration of the microbes in soil is indicative of greater activity of the soil microbes present which contribute to organic matter decomposition and nutrient cycling (Evanylo and McGuinn, 2000, Haney et al., 2008). A 24 hour CO_2 release highly correlates with other methods of soil respiration such as microbial biomass (Haney et al., 2008). Moisture, temperature, oxygen, soil pH, and available substrates can impact soil respiration as well as practices that lead to loss of soil habitat such as tillage or addition of chemicals such as fungicides targeted for pathogenic organisms (Evanylo and McGuinn, 2000). Because soil respiration is a process tied to both carbon mineralization and decomposition, it provides benefits and drawbacks yet sustainability of the organic matter must be maintained. For this reason, higher respiration rates are not always representative of a healthy soil ecosystem, but they are indicative of strong microbial activity. Identifying an optimal level associated with a natural, undisturbed condition may be appropriate (Evanylo and McGuinn, 2000, NRCS, 2018).

Enzymes β-glucosidase and β-glucosiminidase

These two enzymes are substrate-specific and reflect the ability of a soil to decompose organic matter and release N into plant available forms (Alkorta et al., 2003). Enzyme activity can source from dead microbes, residues, and animals, and hence, concentrations of soil enzymes can estimate long term microbial activity and respond to changes in soil management more quickly than many other indicators that slowly degrade such as total carbon loss ((Tabatabai, 1994, Dick et al., 1994). Higher values of these enzymes are associated with healthier soils more capable of recycling C and N and organic matter stabilization (Das and Varma, 2010, Bandick and Dick, 1999). Enzyme function may be inhibited by chemicals introduced to the soil by pesticide application and can result in problems with plant nutrition (Alkorta et al., 2003).

Hot water extractable organic carbon

Hot water extractable carbon is associated with aggregate formation, a reserve of nutrients and energy for plants and microbes, as well as biological activity. The procedure lyses microbe cells and releases biomass components and non-biomass substances which relate well with microbial biomass C (Sparling et al., 1998, Ghani et al., 2003, Hamkalo and Bedernichek, 2014, St. Luce et al., 2016). Water extractable carbon measurements reflect changes in labile soil organic matter caused by intensive agricultural practices which reduce microbial biomass and microbial activity. (Hamkalo and Bedernichek, 2014). Higher values of hot water extractable organic C are representative of greater soil health as they relate to critical soil functions of carbon storage and soil biodiversity.

Potentially mineralizable nitrogen (PMN)

The conversion of nitrogen from complex organic forms into ammonium (mineralization) is a biological process in which nitrogen becomes plant available. Various microbial groups convert these molecules into ammonium and nitrate by mineralization and nitrification which plants can then uptake (Moebius-Clune et al., 2016). Higher values of PMN increase plant nutrient availability and contribute to overall enhanced microbial growth and activity such as C and N cycling (NRCS, 2018, Doran, 1987, Drinkwater et al., 1996). Thus, higher PMN is often correlated to greater soil health (Karlen et al., 2001m, Moebius-Clune et al., 2016).

Table 2.16 Summary of general indicator interpretation with supplemental soil fertility data.

Indicator	Interpretation
Physical Indicators	
Water holding capacity (%)	Higher is better
Water stable aggregates (%)	Higher is better
Chemical Indicators	
Total organic carbon (%)	Higher is better
C:N (ratio)	Depends on crop/soil type
Biological Indicators	
CO_2 burst (mg C kg^{-1})	Higher represents more active microbial community
Mineralizable nitrogen (mg kg^{-1})	Higher is better
β-glucosidase (mg kg^{-1})	Higher is better
β-glucosiminidase (mg kg^{-1})	Higher is better
Hot water extractable organic C (mg kg^{-1})	Higher is better
Fertility/Nutrients	
pH	6.0—7.0 is ideal
Base cations ($cmol_c$ kg^{-1})	Depends on crop
Available phosphorus (mg kg^{-1})	Depends on crop, but > 100 mg kg^{-1} signifies excessive

Management effects on soil health indicators

A gradient of differences in soil characteristics related soil health to soil management, and allowed for identification of the most sensitive indicators for soil health testing (Figure 2.17, Table 2.14). In support of these conclusions, the averaged untransformed values of the final indicators within each management group decrease towards management groups on the right of the spectrum representing lower soil health (Figures 2.23a-i). Due to the characteristically high carbon of the Amalu series Histic Inceptisol (Site R) and unique condition of it as native forest, it is not included as an extreme outlier without data transformation (Appendix C). The relatively clear trend of increased values for management groups with presumed higher soil health for all indicators supports their performance and ability to differentiate across management classes.

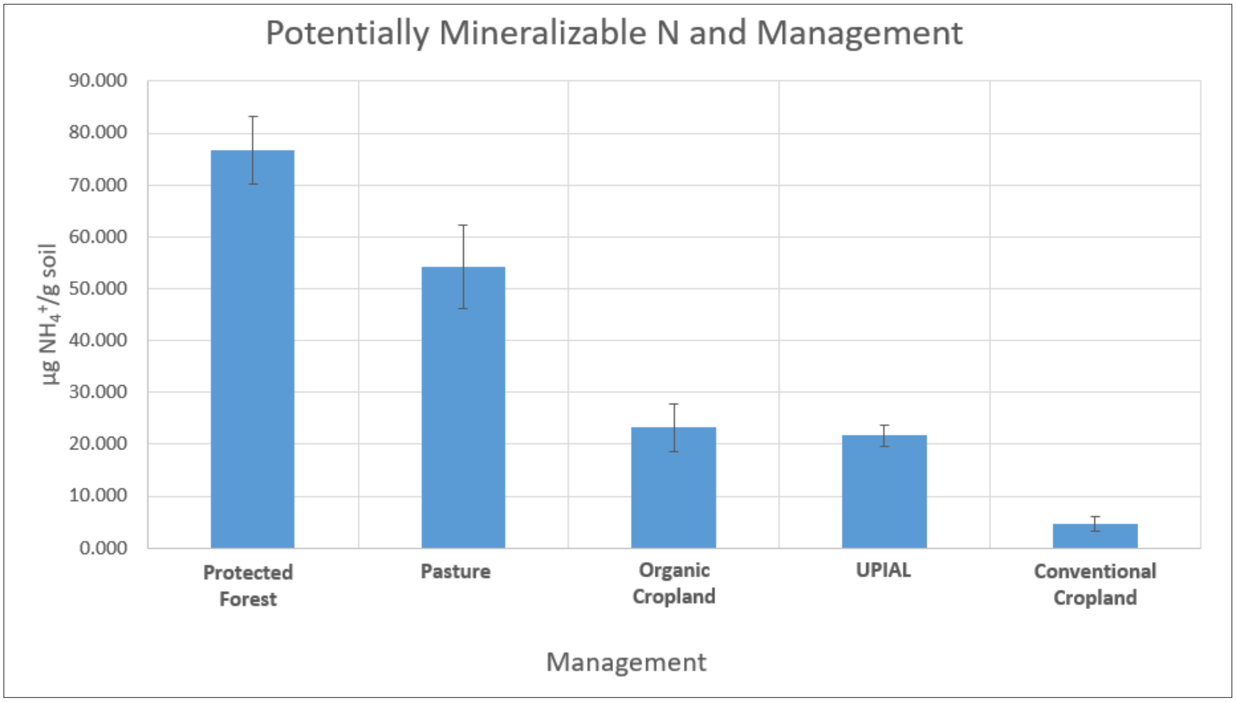


Figure 2.23.a Averaged values within management groups regressed with potentially mineralizable nitrogen, with standard error bars above each data point and R^2 value of 0.93.

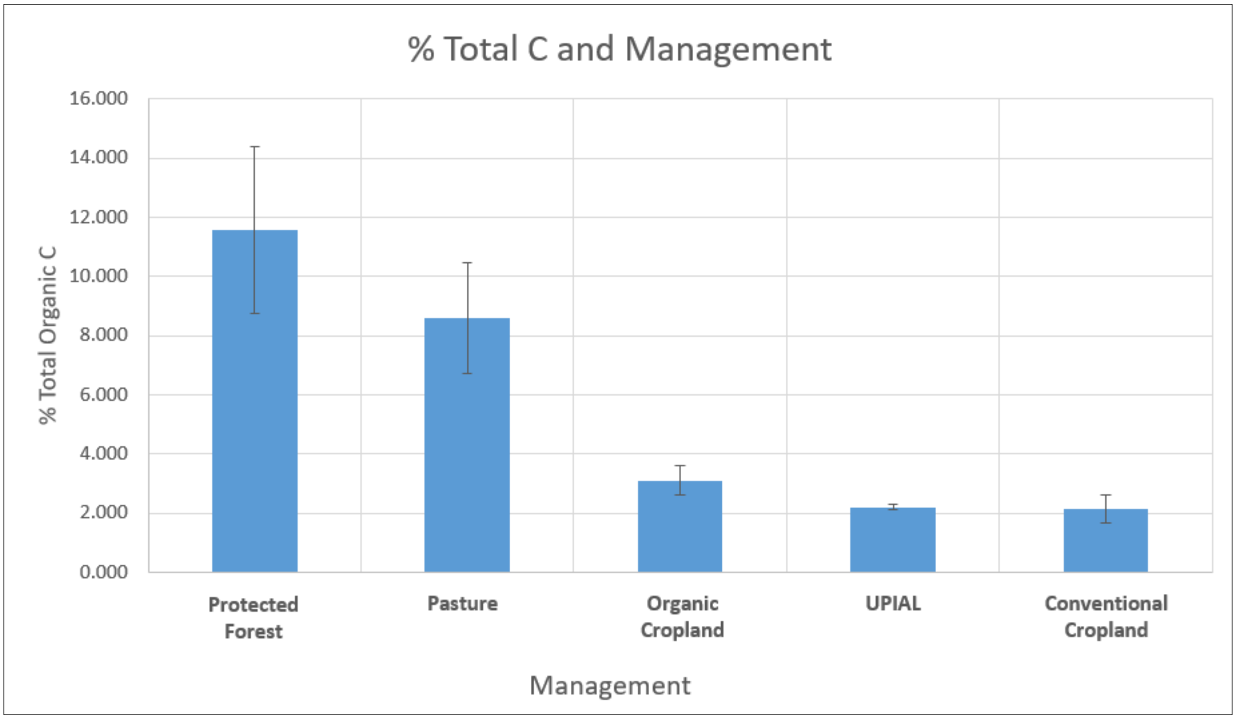


Figure 2.23.b Averaged values within management groups regressed with total organic carbon, with standard error bars above each data point and R^2 value of 0.86.

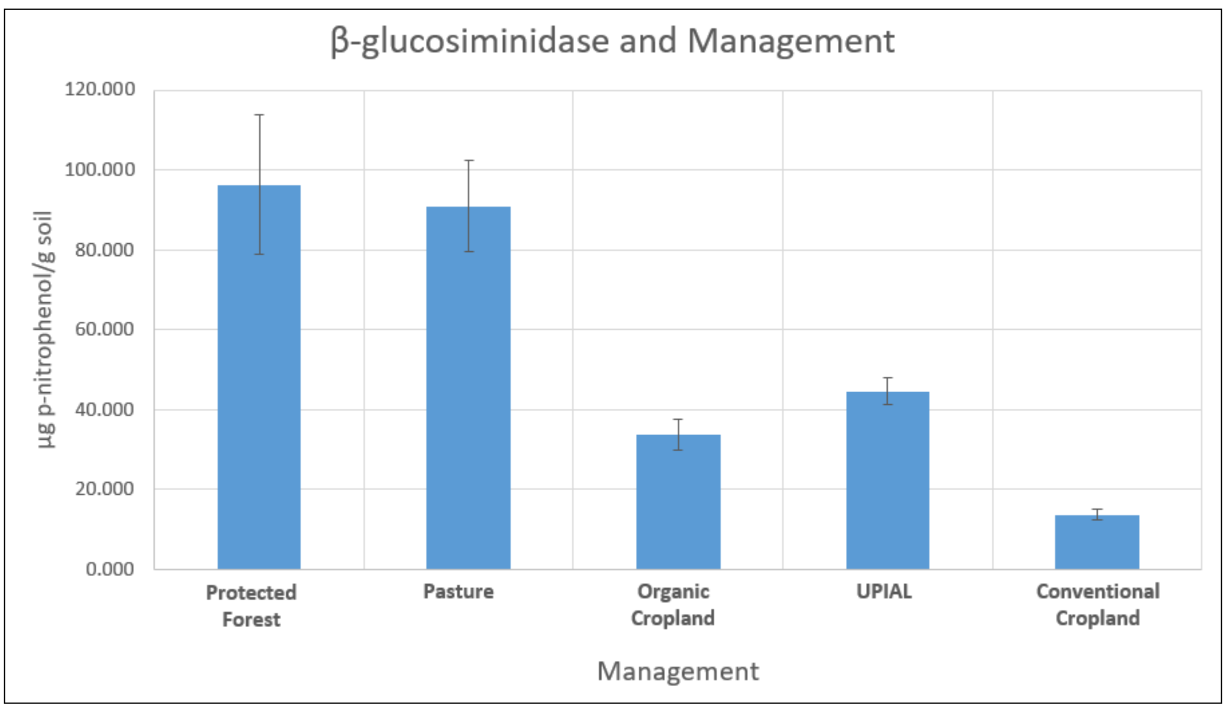


Figure 2.23.c Averaged values within management groups regressed with β-glucosiminidase with standard error bars above each data point and R^2 value of 0.85.

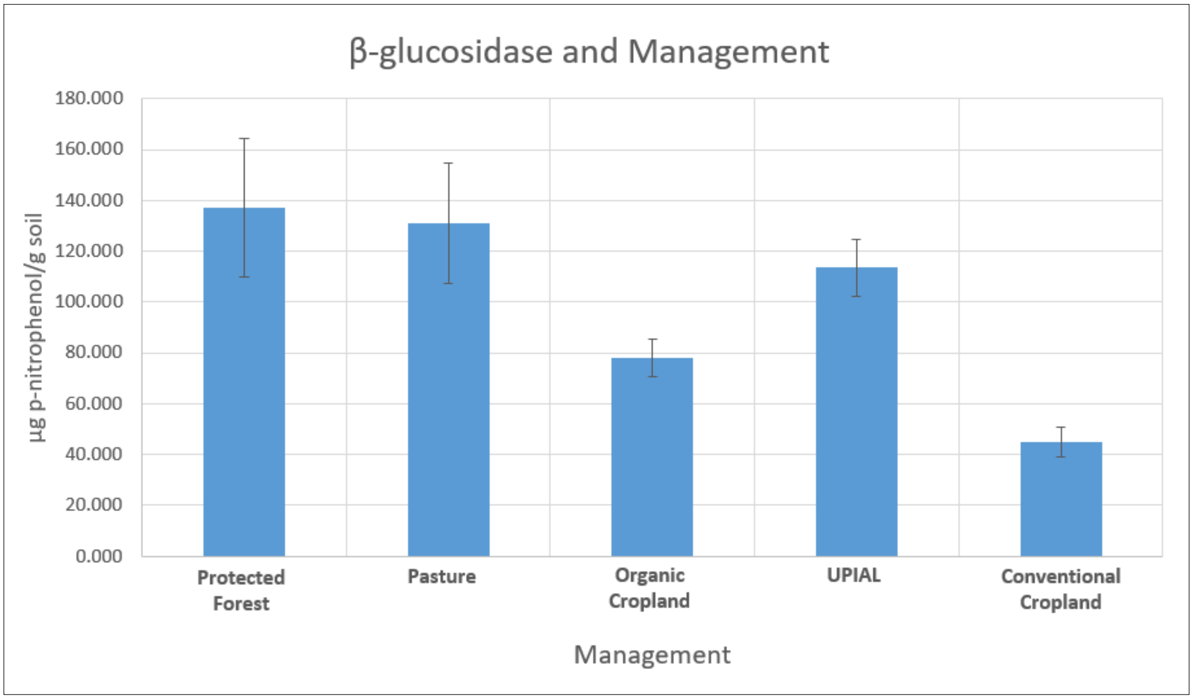


Figure 2.23.d Averaged values within management groups regressed with β-glucosidase with standard error bars above each data point and R^2 value of 0.68.

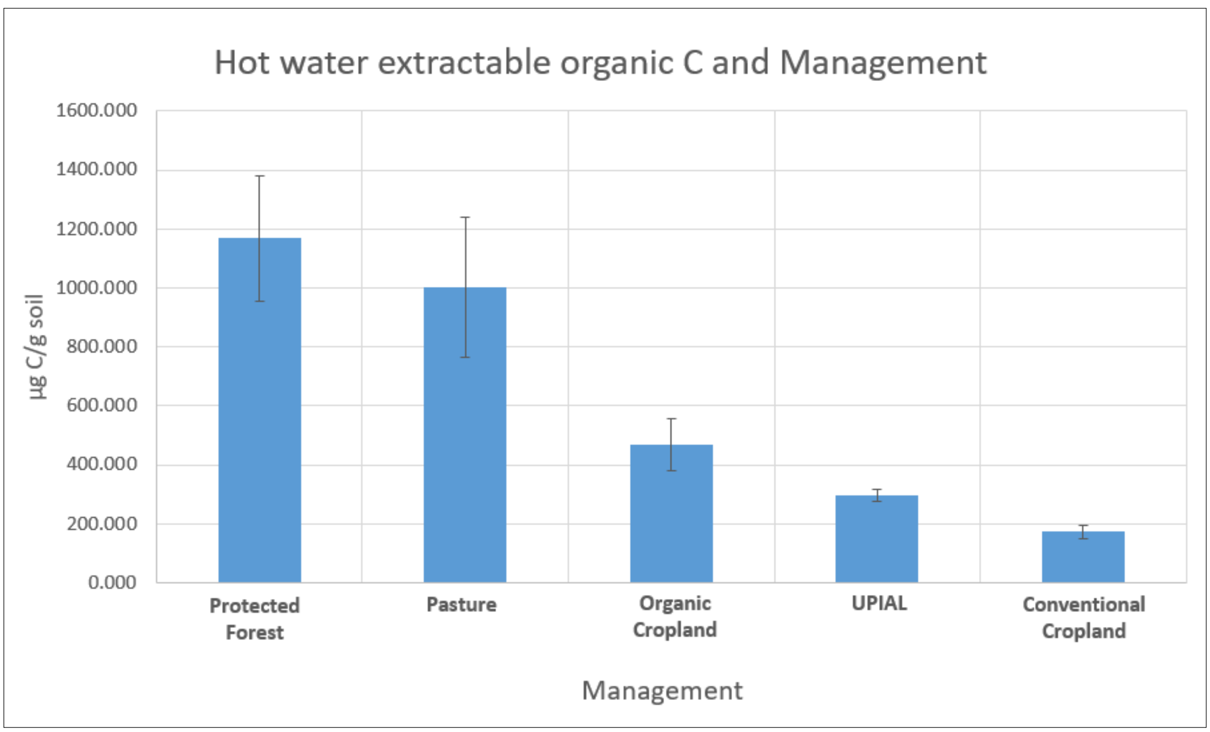


Figure 2.23.e Averaged values within management groups regressed with hot water extractable organic carbon, with standard error bars above each data point and R^2 value of 0.94.

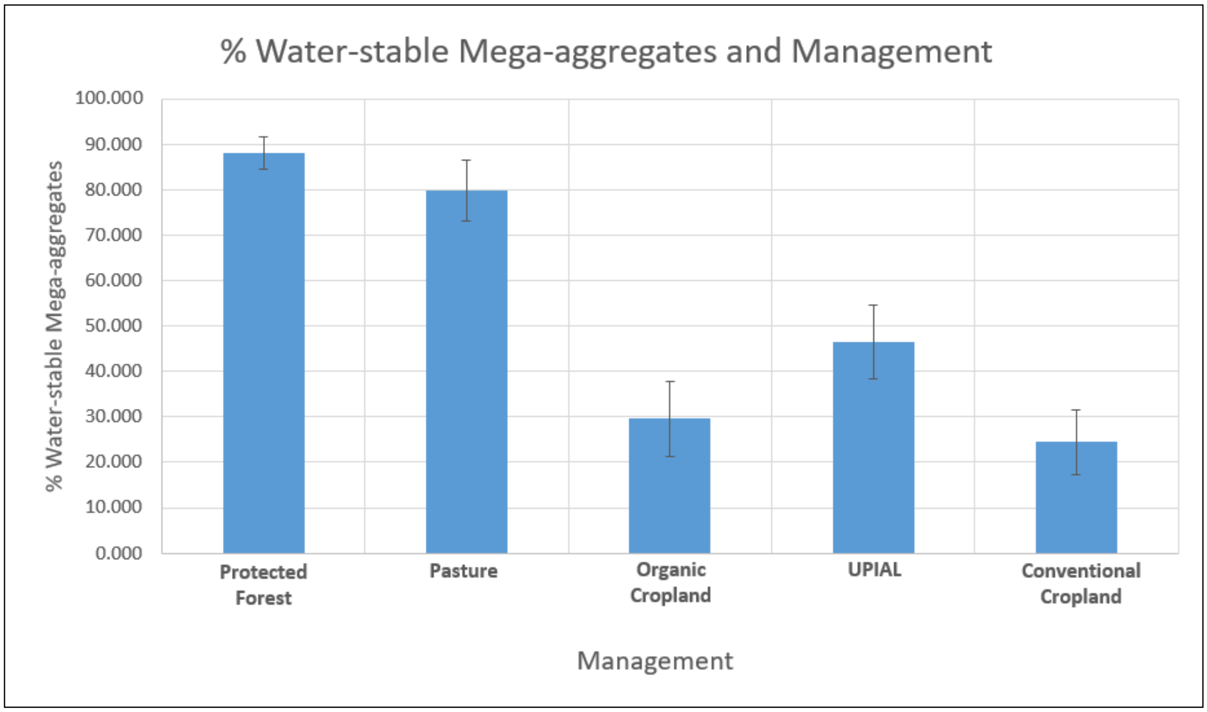


Figure 2.23.f Averaged values within management groups regressed with water-stable mega-aggregates, with standard error bars above each data point and R^2 value of 0.77.

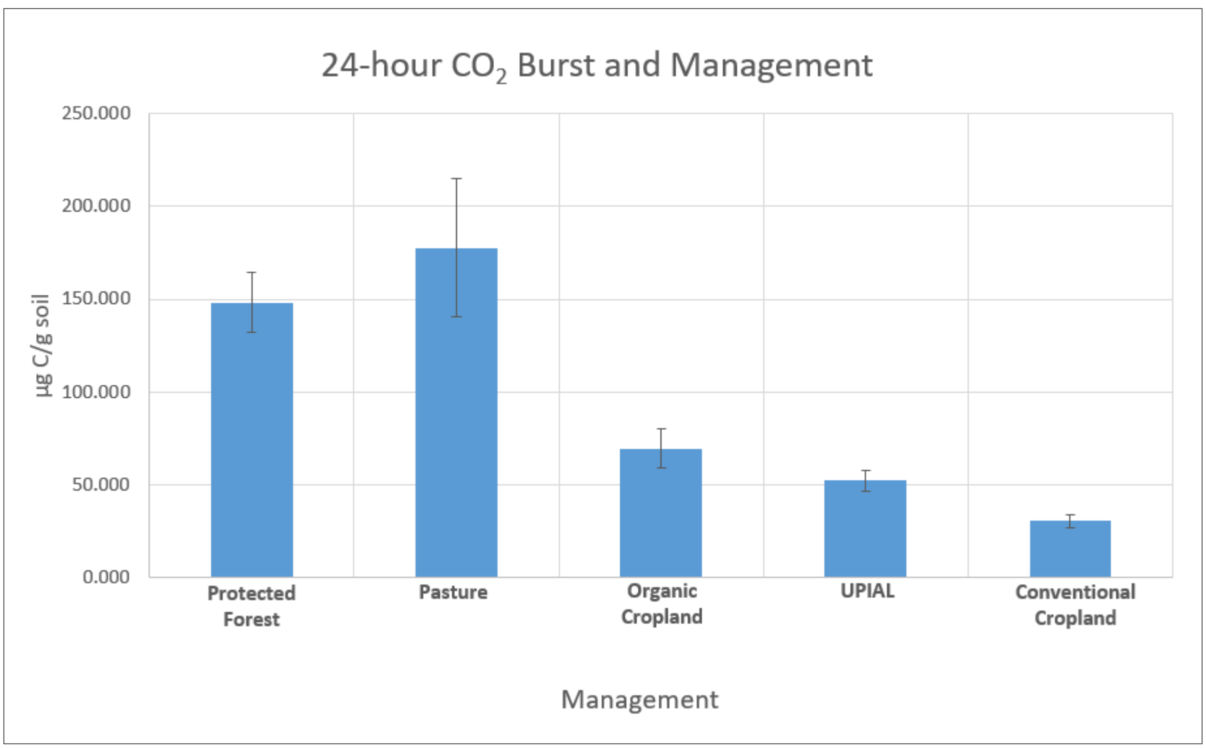


Figure 2.23.g Averaged values within management groups regressed with 24-hour carbon dioxide burst, with standard error bars above each data point and R^2 value of 0.80.

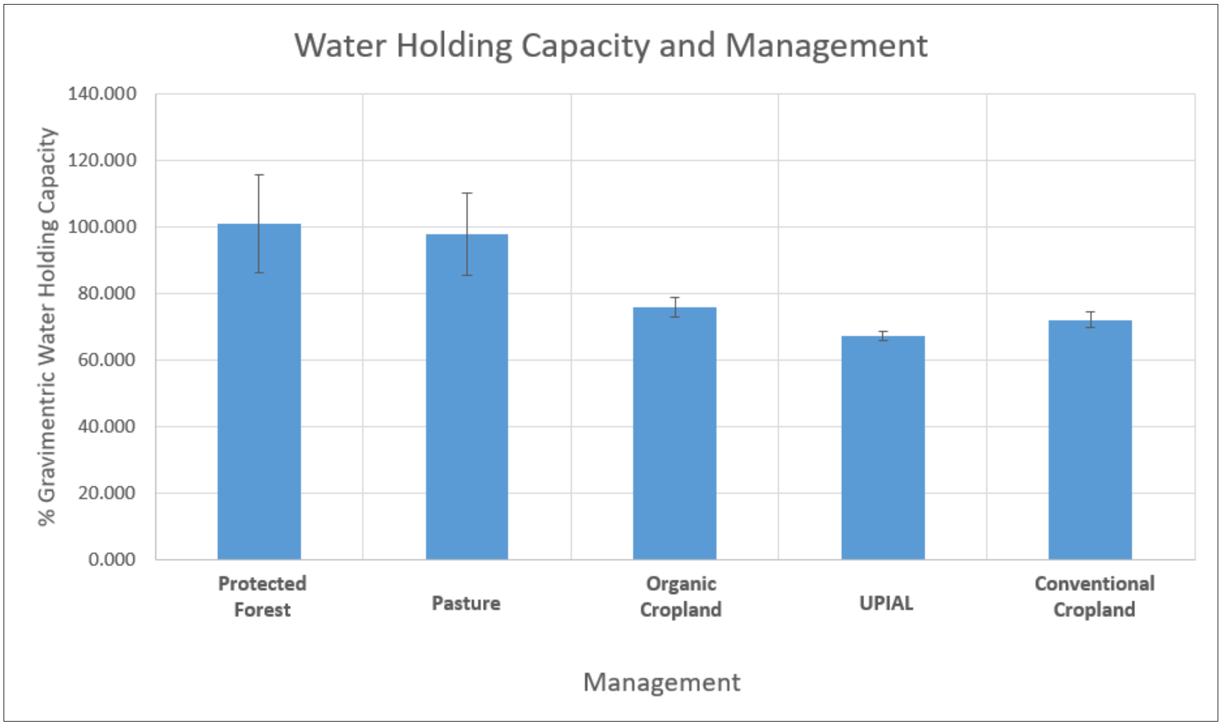


Figure 2.23.h Averaged values within management groups regressed with water holding capacity, with standard error bars above each data point and R^2 value of 0.81.

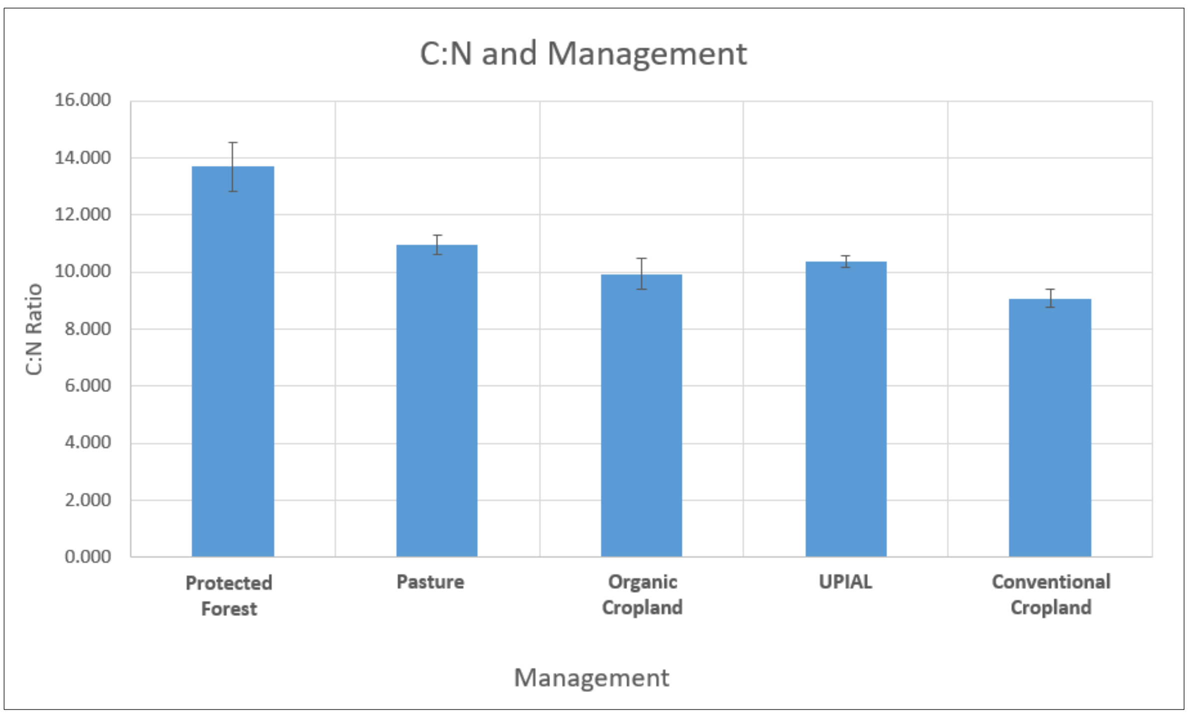


Figure 2.23.i Averaged values within management groups regressed with C:N, with standard error bars above each data point and R^2 value of 0.78.

Soil disturbance and management impact on ecosystem balance

The nine indicators selected for soil health testing supported the observed trend of a soil health gradient related to management, including considerable impact related to the degree of disturbance (Figure 2.17, Figures 2.23.a-i). Evaluating the soil function these indicators represent with the implications of various management can then be used to better understand the association of management and disturbance to overall soil health.

While there are exceptions, the level of disturbance in each management category is generally predictable unless specific sites are making considerable efforts to further reduce disturbance or are adding excess disturbance. Intuitively, forest lands experience little to no disturbance. For UPIAL sites, disturbance level is medium with 10+ years of a land not in agricultural use. However, it is apparent that there is a considerable remaining impact from such previous disturbance as it separates those sites far from the low disturbance sites, and comparable to the high and very high disturbance sites. Cropland sites are all considered very high disturbance since both organic and conventional methods add significant soil disturbance by tilling multiple times a year and may also be compacting the soil with farming machinery. For the most part, management categories captured the level of disturbance as well.

The gradient of soil characteristics related to soil health aligning with disturbance and hence management patterns is likely primarily due to significant loss of soil life and sufficient soil structure to support such life (Moebius-Clune, 2016). Management practices associated with those management groups on the less-optimal end of soil health often damage the soil via compaction, tillage, pesticide application, and harvesting mechanisms. Compaction reduces the space between soil particles where air and water are held which are crucial components to supporting soil life and plant health (Moebius-Clune, 2016). Frequent tillage breaks soil aggregates which typically benefit to increase water infiltration, water storage, gas exchange, and erosion resistance (Beare et al., 1994, Arai et al., 2014) Pesticides are standard practice in conventional management and the overuse of them in intensive agriculture kills necessary microbes and can also inhibit the ability of soil enzymes to cycle nutrients sourced from organic substrates (Alkorta et al., 2003). Harvesting crops often requires the removal of the living roots that support a rich microbial ecosystem in the rhizosphere (soil ecosystem near plant roots) and can deplete the soil carbon if there are no additions of organic matter such as compost (Walker, 2003, Rasse et al., 2005).

The lasting effects from intensive agriculture practices resulting in losses of microbial biomass, enzyme function, carbon, and degradation of soil structure, are observed in UPIAL sites. The time required to reaccumulate lost carbon as well as the loss of soil enzymes which assist in nutrient cycling, may explain the significant lag in UPIAL soil recovery to higher indicator values more comparable to a pasture grassland or undisturbed forest. Enzyme presence and their full function may be restored slowly due to previous pesticide applications and loss of microbes, animals, and organic matter (Tabatabai, 1994). Flourishing life is expected in a landscape that has been undisturbed for many years, such as non-UPIAL grassland and forest sites, if it were not for the apparent long term damage of previous land use (Menta, 2012, Alkorta et al., 2003).

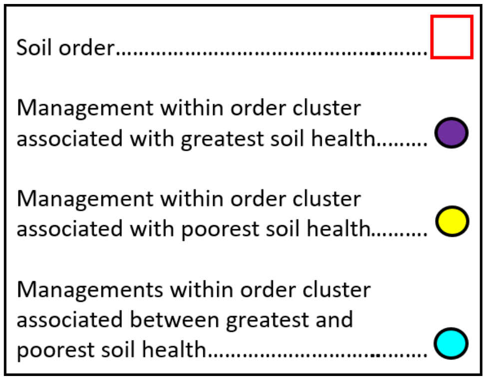
Without restoration efforts to assist in building soil organic matter and soil life, we cannot anticipate rapid improvement of soil health in abandoned or unmanaged lands. From the management gradient, we see that organic management holds slightly greater potential for soil health than UPIAL or conventional cropland, under the same or similar levels of disturbance (Figure 2.17). Typical organic management practices such as limiting pesticide use and adding organic matter, which benefit soil the soil ecosystem, offer some support as to why organic management may score more favorably among soil health indicators compared to those of UPIAL and conventional sites (Awale et al., 2017). However, these changes of improving health of the soil ecosystem are not rapid and may take significant time to improve overall soil health and provide benefits to the farmer (Karlen et al., 2008).

2.4.7 The role of taxonomy in soil health testing

Soil order impact on selected soil health indictors

The proposed sensitive indicators of soil health also display potential to detect differences in soils when grouped by soil order, further supporting their relevance to representing differences across soil diversity relating to soil health. Comparing like to like more effectively challenges the power of indicators in their sensitivity to management change since the behavior of soils between orders, while not a dominant axis, can be considerably impacted by pedogenic effects that make soils intrinsically different regardless of management (Beare et al., 1994). In Figures 2.24.a-i, the end points of the soil health gradient by management are highlighted within each soil order (Figure 2.24). Generally, the management groups are associated with their corresponding less ideal or more ideal calculated values for each parameter relating to soil health. A top sensitive indicator, the 24 hour CO_2 burst, demonstrates well how a soil health gradient by management can exist within each soil order and how values between orders aren't necessarily comparable (Figure 2.24.a). For example, the optimal management of Vertisols within the dataset (organic), while having higher scores for this indicator and many indicators than the less-optimal management groups (conventional and UPIAL), still has values less than comparable management types of other soil orders. The Mollisols notably do not follow this pattern and instead show the opposite pattern of sensitivity, with the conventional plot indicating higher potential soil health than its organic counterpart for most indicators (refer to Section 2.4.3 on notable sites, cropland). Despite the small sample size per soil order, Figure 2.24a-i suggests that the indicators are able to detect differences between varied management. The qualitative assessment of indicator sensitivity within and across soil order highlights the importance of how taxonomy affects soil health and hence its notable impact on PCA and association to Axis 2.

Figure 2.24 Legend corresponding to Figures 2.24.a-i. Sites of the same soil order are grouped with a red box. Using the soil health gradient from Figure 2.17, the management group within the order on the least optimal of the gradient is identified with yellow, the group on the optimal end identified with purple, and all groups that fall between optimal and least optimal soil health are identified with blue.



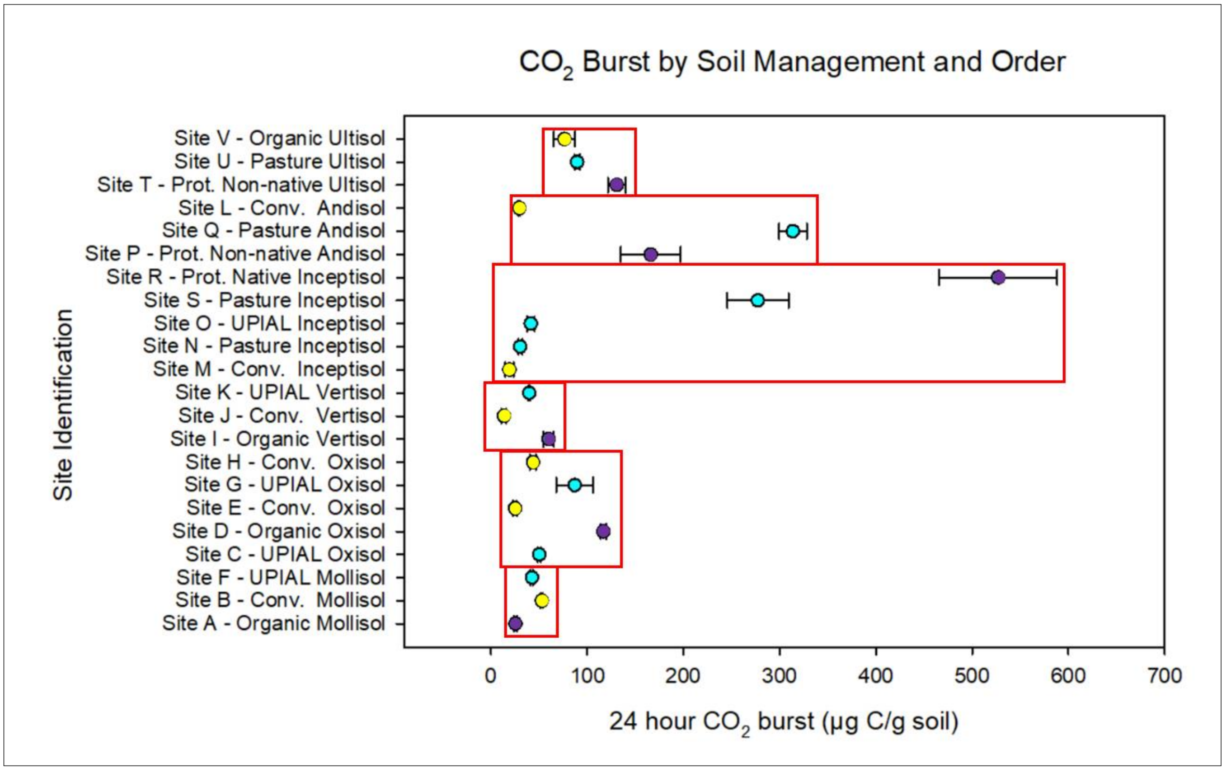


Figure 2.24.a Site averages with standard error bars for CO_2 burst grouped by order.

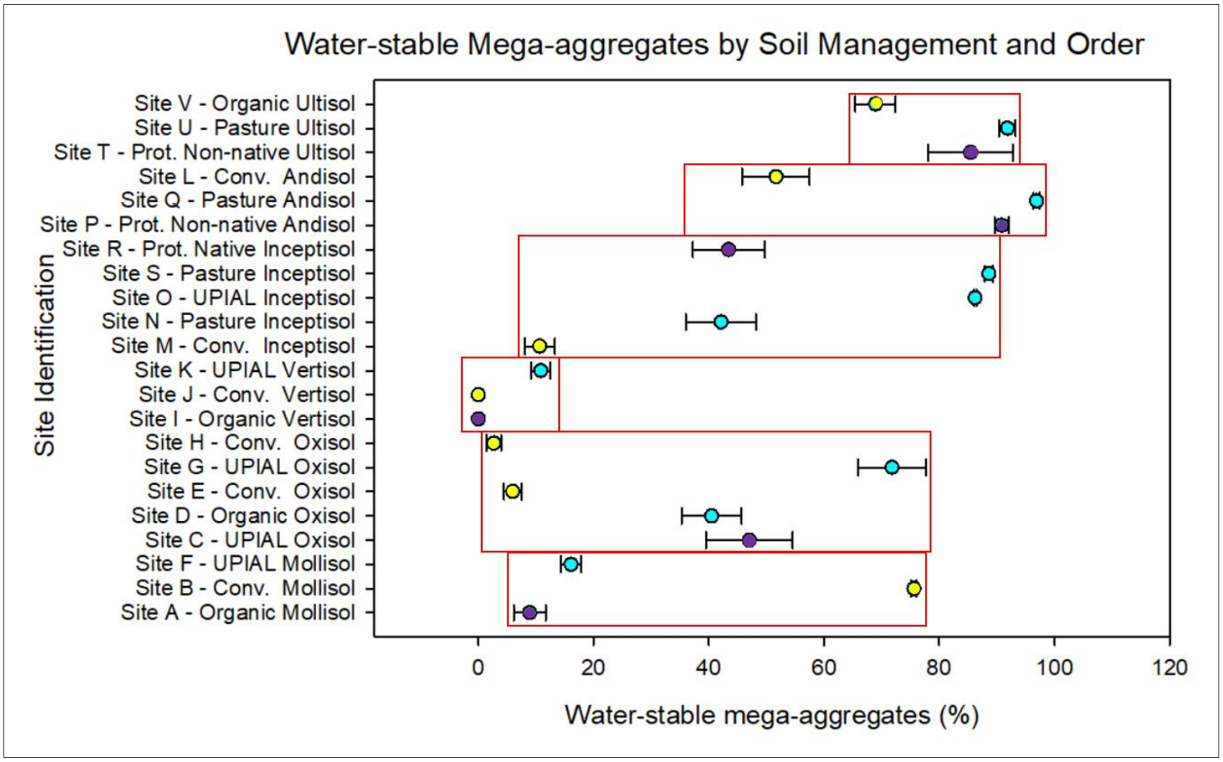


Figure 2.24.b Site averages with standard error bars for water-stable mega-aggregates grouped by order.

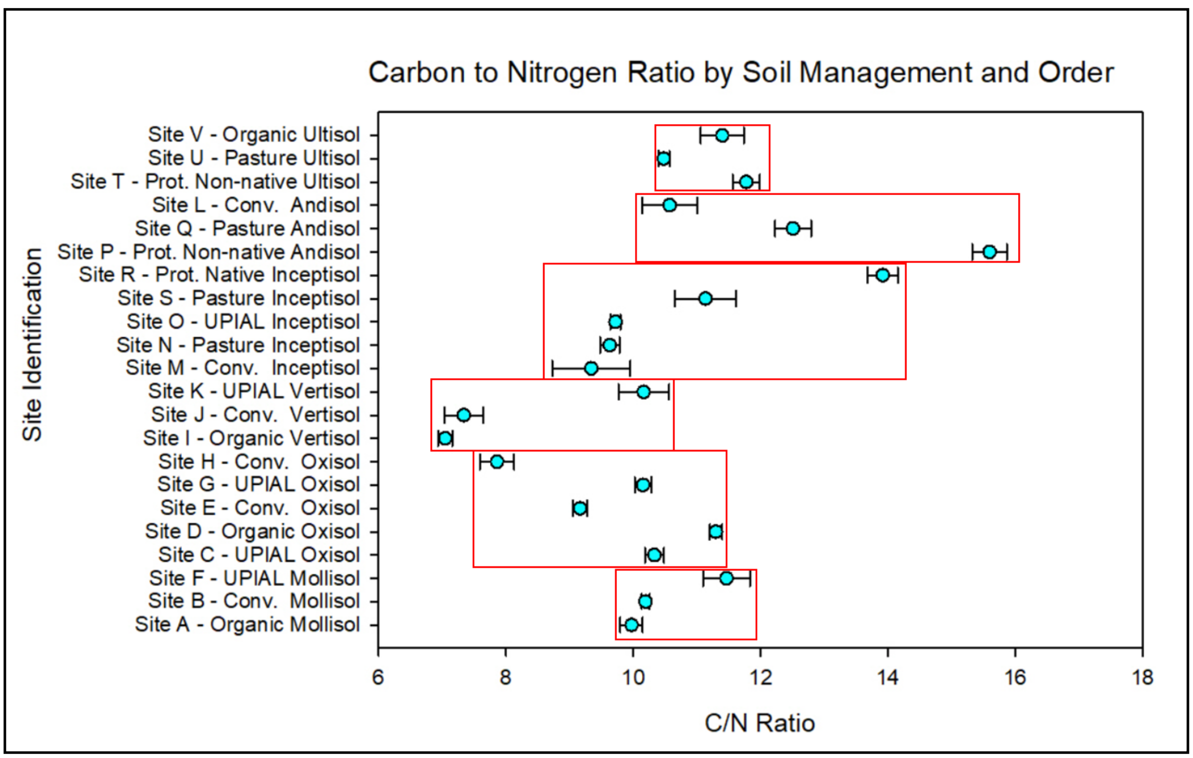


Figure 2.24.c Site averages with standard error bars for C:N grouped by order.

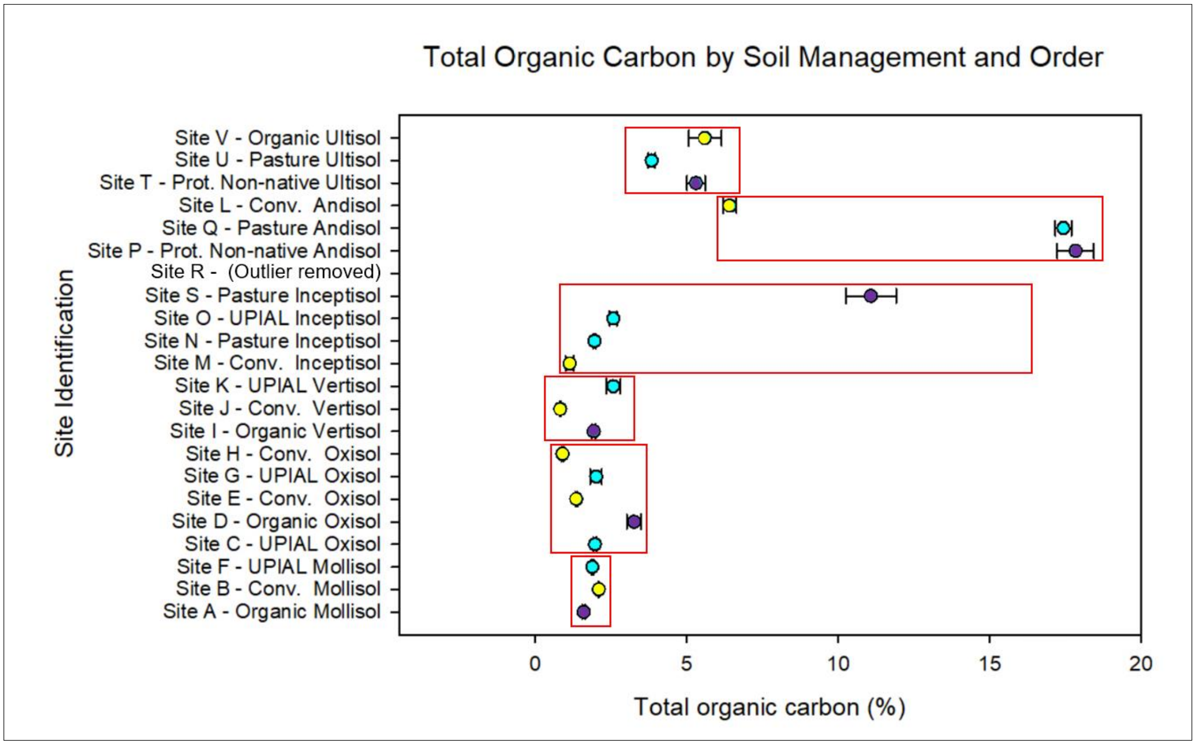


Figure 2.24.d Site averages with standard error bars for total organic carbon grouped by order.

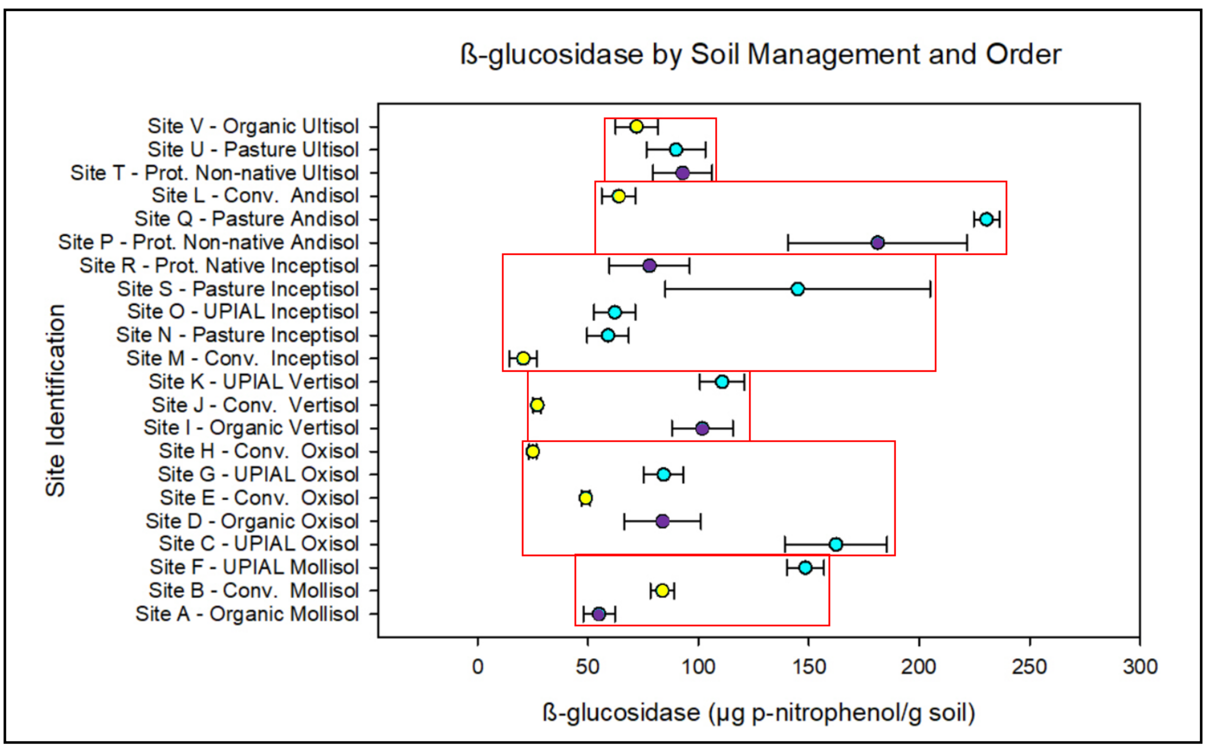


Figure 2.24.e Site averages with standard error bars for β-glucosidase grouped by order.

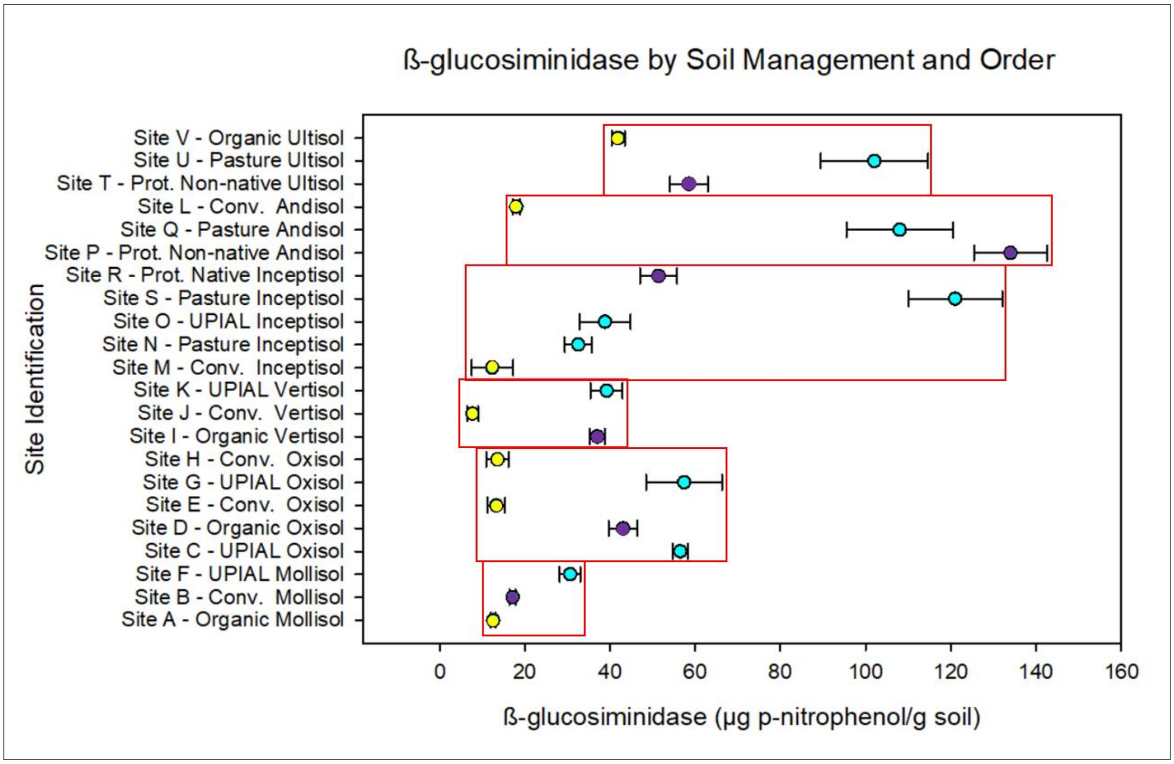


Figure 2.24.f Site averages with standard error bars for β-glucosiminidase grouped by order.

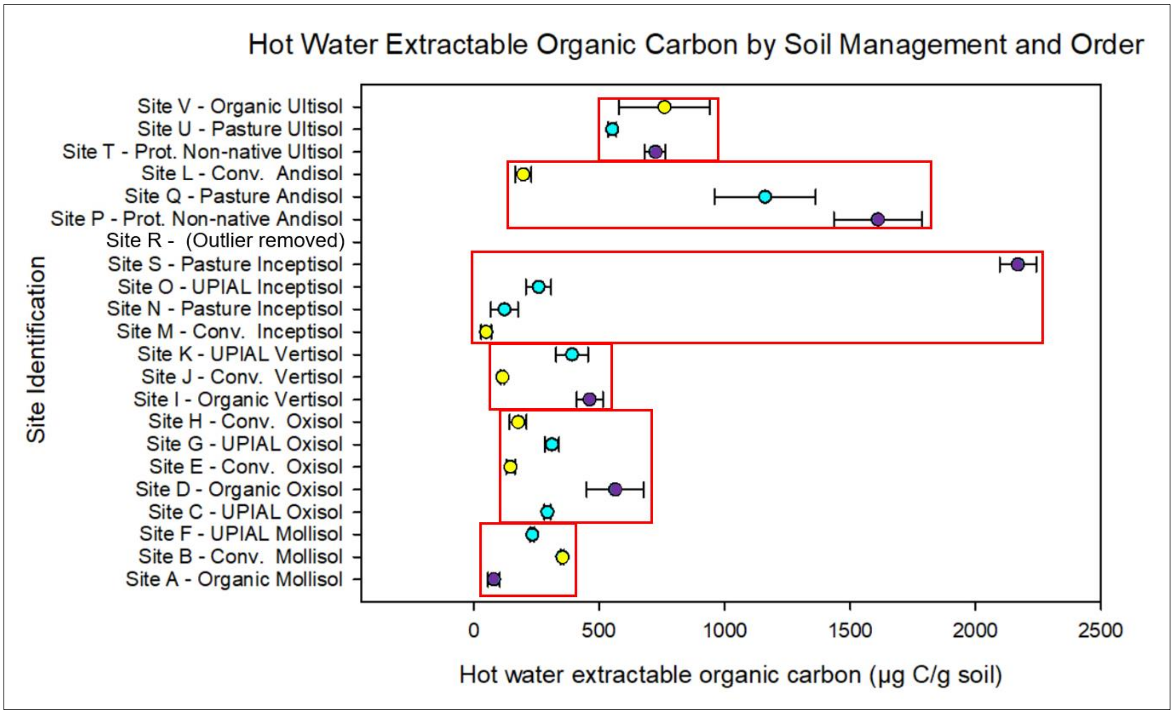


Figure 2.24.g Site averages with standard error bars for hot water extractable organic carbon grouped by order.

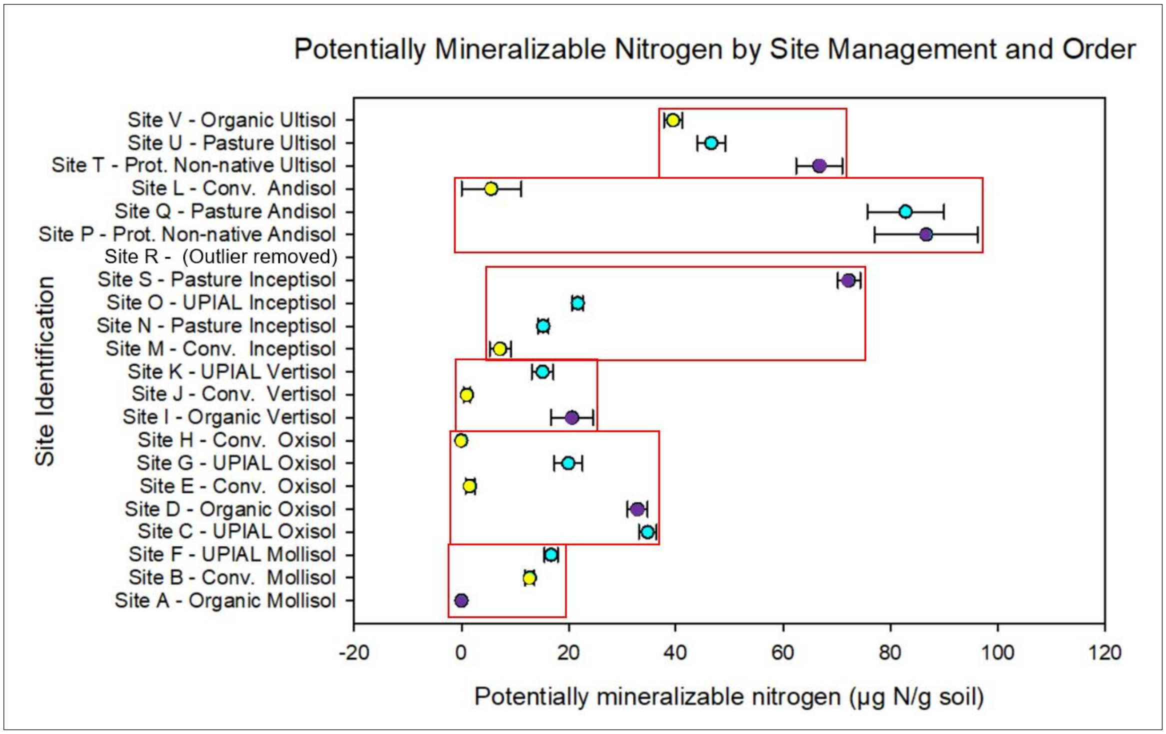


Figure 2.24.h Site averages with standard error bars for potentially mineralizable nitrogen grouped by order.

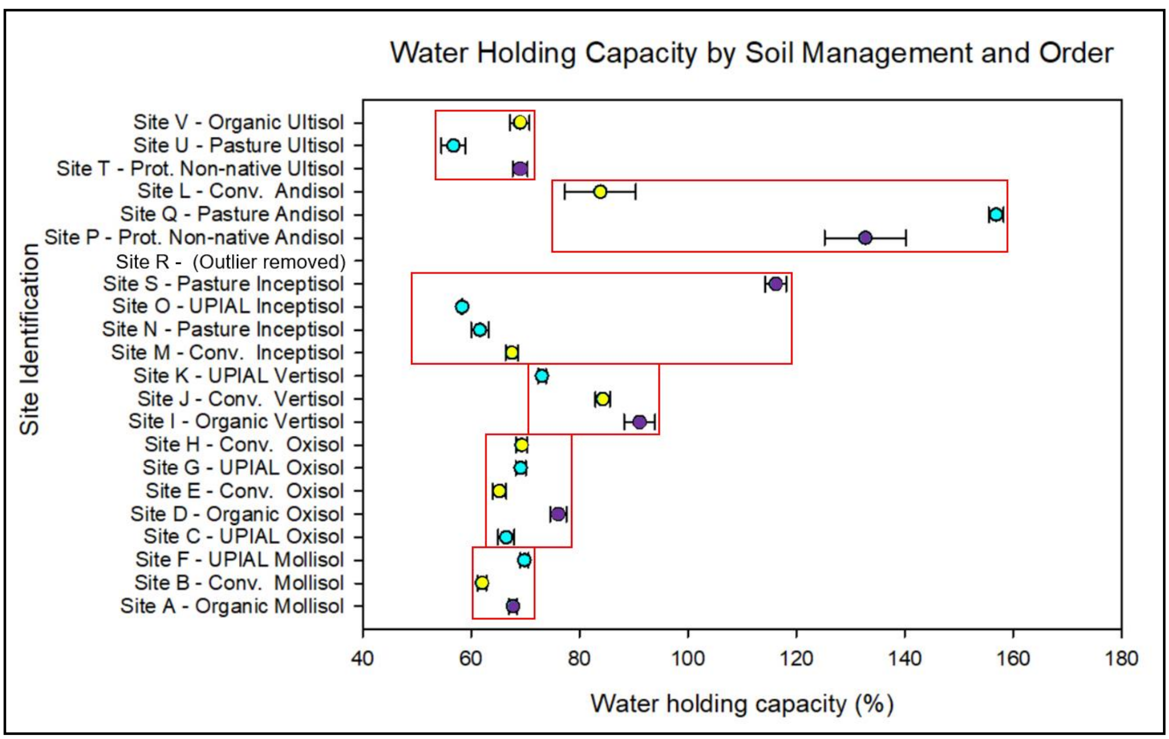


Figure 2.24.i Site averages with standard error bars for water holding capacity grouped by order.

Figures 2.24.a-i The untransformed parameter values of the reduced set of indicators show qualitative differences between the soil management/disturbance gradient when grouped by soil order. Soil orders are grouped within red boxes and the management groups within each soil order that are associated to characteristics in soil parameters related to soil health, and hence to soil health, are highlighted in color. Site R is removed from some graphs (d, g, h, and i) as an extreme outlier without data transformation (Appendix C).

While the impacts of management showed to be the leading determinant of variation in soil health across landscapes, soil taxonomy played a crucial role in the behavior of soil indicator values within orders. In comparing like to like in Figures 2.24a-i, effects of management clearly impact the indicators. However, comparisons of indicator performance between soil orders is misleading if interpreted as a ‘one size fits all’ test. For example, the conventional Andisol (Site L) would be interpreted to have a similar or “higher” soil health score using most sensitive indicators, such as total organic carbon, than some of the pasture or organic management types of other soil orders sampled (Figure 2.24.d). Andisols are typically rich in amorphous material and as a result of high surface area have the ability to hold high amounts of carbon which, in addition to total carbon measurements, can positively impact indicators such as water holding capacity, hot water extractable carbon, and soil aggregation. These qualities may be ideal for the goal of improving soil health to sequester more carbon, for example, but it cannot be deduced then that Andisols are healthy and Oxisols are not. Overall, the clusters of soil order must be identified and before comparative soil health assessment.

Ideally with a more robust data set, a soil health test would be developed for each soil order to capture the unique impacts upon soil health parameters. With the current available dataset, most soil orders are represented by a total of three sites with varying management (e.g., nine plots sampled), and so low sample sizes limit the ability to develop a list of sensitive indicators within soil order using separate PCA. Instead, the current dataset is useful to explore the sensitivities of indicators across the landscape and capable to differentiate upon management. To determine the values of each selected indicator that represent the high and low ends of an index scoring system within a soil order, a larger number of samples is necessary and recommended to further develop indicator sensitivities tailored for soil order groups.

2.4.8 A recommended tiered system approach to soil health testing

With high potential variability among soil types and management, a ‘one size fits all’ soil health index is not a suitable approach for Hawai‘i. The final indicators for soil health assessment are recommended to be used in conjunction with soil taxonomy. Inherent soil differences are crucial to assess before setting realistic goals of measured soil health values. Then, overall soil management goals can be appropriately identified and compared to sites of similar soil type (Figure 2.25). The accuracy and applicability of a Hawai‘i soil health index will be continually optimized as the dataset is expanded with continued research, and optimal values of each indicator can be tailored to environmental variation.

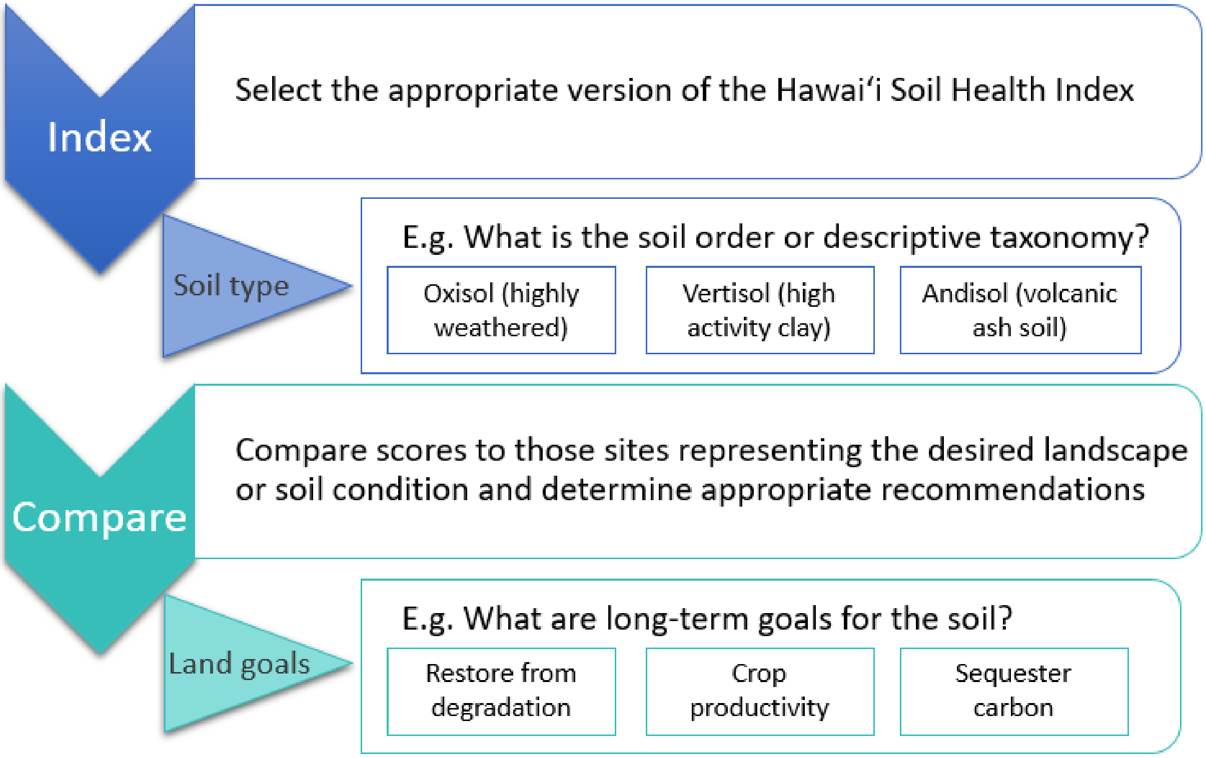


Figure 2.25 A conceptual map of a recommended tiered system approach to soil health testing, which addresses the factors impacting goal setting and variability in soil health test results.

A case study of management effect in Oxisols

Three sites of the same Oxisol soil series under different long-term management offer a case study example for the application of a soil health test (Table 2.17). Two of the sites are managed as cropland systems (organic versus conventional) and the third site is a UPIAL site that has not been under cultivation for at least 10 years and is a reasonable example of the health of this soil type when under uncultivated conditions (Figure 2.25). While unitless weights of a soil health index are not yet developed to apply to these site indicator scores for one overall score for each site, indicator values between the two sites can still be compared using the guidelines of "higher is better," "lower is better," or "optimal value," regarding increasing soil health (Table 2.16). Ideally with the recommended tier system, these soils would use a soil health index calibrated for reasonable optimal values within the taxonomic group of Oxisols. Comparing the two managed farms with the UPIAL site with supplemental information from fertility testing demonstrates the benefits of organic farming on soil health, and can also help highlight where improvements can be made on the conventional farm to increase soil health as well as assess any unnecessary costs associated with excessive nutrient application.

Table 2.17 Averaged parameter values (standard error in parentheses) of selected indicators and supplemental fertility data for Oxisols under organic, conventional, and UPIAL management.

OXISOLS			
Soil Qualities	Organic	Conventional	UPIAL
Physical Indicators			
Water holding capacity (%)	76.1(± 1.5)	65.2(± 1.2)	66.5(± 1.5)
Water stable aggregates (%)	40.5(± 5.2)	6.0(± 1.6)	47.1(± 7.5)
Chemical Indicators			
Total organic carbon (%)	3.25(± 0.24)	1.35(± 0.04)	1.97(± 0.06)
C:N (ratio)	11.3(± 0.1)	9.2(± 0.1)	10.3(± 0.2)
Biological Indicators			
CO_2 burst (mg C/kg)	116.7(± 2.9)	24.9(± 1.8)	50.1(± 1.6)
Mineralizable nitrogen (mg/kg)	32.8(±1.9)	1.6(± 0.9)	34.8(±1.7)
β-glucosidase (mg/kg)	83.8(± 17.3)	49.0(± 1.9)	162.3(± 23.1)
β-glucosiminidase (mg/kg)	43.1(± 3.4)	13.3(± 2.1)	56.5(± 1.8)
Hot water extractable organic C (mg/kg)	563(± 114)	146(± 18)	293(± 13)
Fertility/Nutrients			
pH	6.77(± 0.15)	5.33(± 0.10)	6.79(± 0.04)
Base cations (mg/kg)	9.20(± 1.90)	1.52(± 0.08)	3.73(± 0.03)
Available phosphorus (mg/kg)	82.5(± 39.6)	78.0(± 2.2)	21.7(± 21.4)

The various management groups of these Oxisols exemplify expected trends of change across the physical, chemical, and biological indicators of soil health. Water-stable aggregates

are highest in the UPIAL soil likely due to reduced soil disturbance (tillage) and lowest in the conventional soil, likely attributable to the loss of organic matter. Considering such low current values, even small increases in water-stable aggregates of the conventional soil have the potential to benefit soil function by reducing loss of soil to erosion and increasing water infiltration.
The soil biological life relies greatly on the presence of organic matter and the loss of which in the conventional management is also demonstrated. In contrast, organic matter inputs, rich in microbes as well as a source of carbon, in the organic and UPIAL management are likely responsible for higher values for all microbial activity and enzyme indicators representing greater soil health. Such inputs continually added to the organic system have resulted in a considerable increase in total organic carbon and hot water extractable organic carbon compared to the other sites. Lastly, relatively high values of phosphorus in both cultivated soils suggest that continued application of P inputs are not necessary to maintain crop growth which can help farmers reduce the costs of crop production. Continual use of compost and organic matter can contribute to the buildup of base cations and available phosphorus as well as a source of carbon that feed microbes and important in soil aggregate formation and maintenance. From the example of these Oxisols, a recommended step of improving overall soil health would be to build soil organic matter as it positively impacts many of the observed indicator differences, however, it requires substantial and diligent applications over time to continually aggrade the soil health.

A case study of disturbance effect in Inceptisols

Three Inceptisols (Haliimaile series) on Maui demonstrate the effect of disturbance level on soil health. (Table 2.18). Comparing values from a conventional site (disturbance level = very high), a pasture with recent agriculture history (disturbance level = high), and a long-term pasture (disturbance level = low) suggest that the long-term pasture has the highest health and the conventional site the lowest. While two of these sites are currently managed with the same goals and with the same current practices and vegetative cover (forages), the legacy of previous conventional management is evident in the newly-converted pasture site. For example, overall carbon is low in the conventional system when compared to the undisturbed long-term pasture ecosystem with a total organic carbon value approximately 10 times higher (Table 2.18). Overall there are increases in nearly all indicator values from conventional to short-term pasture, and again increases from short-term pasture to long-term pasture with considerable biological indicator increases. Comparing the UPIAL pasture to the conventional site highlights the potential for aggrading soil health in a relatively short period of time. It is reasonable to assume that the short-term pasture and conventional site would have been very comparable just five years prior, and that in just five years, the pasture site has doubled carbon and microbial indicator values. Historical information on land use regarding disturbance shows considerable impact upon the potential soil health of soils when there are no other clear environmental differences, and emphasizes the importance of including such information to better understand the condition of the land and potential lasting impacts of previous and current management decisions.

Table 2.18 Averaged parameter values (standard error in parentheses) of selected indicators and supplemental fertility data for Inceptisols under conventional, short term pasture proceeding intensive agriculture, and long term pasture management.

INCEPTISOLS			
Soil Qualities	Conventional	Pasture (PIAL)	Pasture (long-term)
Physical Indicators			
Water holding capacity (%)	67.5(± 1.1)	61.6(± 1.6)	116.2(± 1.9)
Water stable aggregates (%)	10.7(± 2.6)	42.1(± 6.1)	88.6(± 0.7)
Chemical Indicators			
Total organic carbon (%)	1.13(± 0.14)	1.95(± 0.04)	11.1(± 0.8)
C:N (ratio)	9.3(± 0.6)	9.6(± 0.2)	11.1(± 0.5)
Biological Indicators			
CO_2 burst (mg C/kg)	19.1(± 4.2)	30.4(± 2.1)	277(± 32)
Mineralizable nitrogen (mg/kg)	7.2(± 2.0)	15.3(± 0.9)	72.3(± 2.1)
β-glucosidase (mg/kg)	20.7(± 6.3)	59.0(± 9.5)	145(± 60)
β-glucosiminidase (mg/kg)	12.4(± 4.9)	32.5(± 3.2)	121(± 11)
Hot water extractable organic C (mg/kg)	48.4(± 20.1)	122(± 54)	2,169(± 73)
Fertility/Nutrients			
pH	5.23(± 0.15)	7.36(± 0.25)	6.36(± 0.06)
Base cations (mg/kg)	5.67(± 0.89)	6.47(± 1.70)	5.90(± 0.64)
Available phosphorus (mg/kg)	8.03(± 0.12)	3.18(± 0.72)	15.8(± 8.3)

2.5 NEXT STEPS AND CONSIDERATIONS

2.5.1 Expanding the database and determining target values of soil health

The next steps in the development of a soil health index for Hawaiʻi will rely on expanding sampling to build a robust dataset that adds to the soil diversity and management practices already established. Additionally, the implementation of on-site field trials evaluating the effect of various soil management practices on soil health is required to help farmer decision-making. With an increase in sample size, differences in values can be more closely attributed to environmental differences such as soil order or management. Testing the efficacy to improve soil health based on management change will provide crucial information to guide farmer decisions for soil health improvement, as well as make connections between crop yield and indicators of soil health. The addition of such a response variable will allow for the development of optimal values for each indicator and the ability to develop an overall score of soil health.

Crop productivity and soil health

Expanding the dataset of indicator changes across management and within soil order will improve the accuracy of a soil health index as well as the applicability among soil and land use diversity, such as cropland specific goals. The measured crop yield from field trials can identify optimal growth goals and assist in determining what actual values of each indicator are associated to optimized crop yield in comparison to a site with poor crop yield and contrasting soil health indicator values. For example, the addition of compost to a site may raise soil health indicator values and by x amount compared to another practice, which is a positive shift in the soil health gradient and beneficial as long as crop productivity is not compromised. The ideals of crop productivity should not be confused with the goals of improving soil health, as improvements in the soil ecosystem may be slow to show a response in crop yield and are targeted to reduce negative impacts of land use on the environment. A farmer's goals may be to maintain high yield and while reducing harmful environmental consequences. Therefore, soil health testing as well as crop yield tracking must both be independently managed and addressed to maintain the practicality of aggrading soil health in a cropland system.

2.5.2 Creating realistic soil health goals

The use of the identified soil health indicators is useful for long term landscape management goals. Forested land was most positively associated with desirable soil health parameter measurements, which suggests that Hawai‘i use forest and undisturbed lands as proxies for optimal soil health goals. Improving soil health in such areas can maximize carbon sequestration, improve water quality, and support biodiversity in Hawai‘i. However, a functional ecosystem contains many types of landscapes. For other systems like grassland and cropland, we look towards similar land cover areas with minimal disturbance to set realistic goals for ideal soil health values. It appears that UPIAL lands, while ‘natural’ in their lack of management, must be carefully selected if used as proxies for ideal soil health for cropland comparisons.

Goals across landscapes

Soil health testing a resource to see how land use change impacts Hawai‘i soil as a natural resource. The top five sensitive indicators from the first PCA, for example, may be weighted more heavily in a landscape-based assessment of Hawai‘i soil health (Table 2.9)

(Karlen et al., 2001, Andrews et al., 2002). As a whole landscape, the interpretation of a soil health index weighted as such could be used to assign value to the land under its current land use and management, and then determine what types of changes may be needed and to what intensity of restoration, to reach policy goals for the state. Effective responses to the degradation of soils must emanate from policy change that pertain to soil management by land managers (Lobry de Bruyn and Andrews, 2016). Providing the data for dynamic interactions of land management and soil health is crucial if the state plans to develop effective soil health policy, currently a considerable foreseeable challenge in Hawai‘i due to lack of any current regulation (Stevens, 2018).

Goals in cropland systems

Sensitive indicators within cropland use may be specifically useful for improving cropland management and developing farmer incentive systems. Focusing on cropland use and integrating sensitive indicators of the second PCA into the greater deduction of sensitive indicators ensured that the interests of farmers is strongly tied to the development of a Hawai‘i soil health index (Table 2.12) (Karlen et al., 2001, Andrews et al., 2002). The ranking of sensitive indicators of the cropland and UPIAL soils from the second PCA, varying slightly from the original PCA (Table 2.9), can also be utilized when the goal of a landscape is to improve soil health and maintain the dominant land cover as cropland. By weighting the highly correlated indicators of the cropland PCA more heavily in a soil health index, a farm manager can potentially better detect changes in soil health as a result of changes in management practice. For example, β-glucosiminidase and potentially mineralizable nitrogen are two of the top five sensitive indicators in a cropland system, yet were not within the top five across the landscape, and so these indicators may be given higher unitless weight when scored into a soil health index focused on cropland soil health management. Similarly, a farmer may choose to focus on integrating management practices that are shown to increase values for β-glucosiminidase and potentially mineralizable nitrogen. Allocating extra weight in a soil health index to sensitive parameters, customized for cropland, can more accurately track changes in soil health and therefore optimally benefit farmers participating in soil health management efforts. Ideally, Hawaiʻi will be able to better support farmer's contributing to improvements in soil health by offering incentive programs that reward farmers who can prove they are aggrading soil health using the developed soil health index. Generally, management practices established to facilitate a shift to the left on the soil health gradient should show aggrading soil health scores across all indicators over time. Independent of incentive programs and coupled with soil nutrient testing and tracking crop yield progress, such recommended management changes can benefit farmers by saving them the time and money inefficient management practices and costs of production.

Paradigm shifts of soil health value and outreach

The extension and outreach efforts in soil health and sustainable ecosystems are an ongoing and important effort, particularly for Hawaiʻi as an isolated island chain with limited resources and sensitivities to climate change. Efforts in expanding social science applications to soil science make the concept of a more self-sufficient Hawaiʻi a realistic goal in the foreseeable future, but will require major boosts in sustainability education and interdisciplinary studies that directly relate to aspects of culture and perceptions which currently impact and limit improving soil health (Appendix A).

2.6 CONCLUSION

Sensitive and practical indicators to soil health testing provide a tool to begin measuring meaningful changes in the soil ecosystem and will support the next phase of indicator development when fine-tuned into unitless scores of soil health. From interpretation of principal component analysis (PCA), current and previous management practices demonstrated high impact and association to what is understood to represent soil health across biological, physical, and chemical soil properties, with soil order acting as a crucial consideration among soil differences. Creating an associated gradient from least optimal soil health to optimal soil health, managements shifted in the respective order of conventional cropland, unmanaged previous intensive agricultural land (UPIAL), organic cropland, pasture land, and protected forest. Nine indicators were identified to best detect changes across the gradient of soil health. Determination of these indicators used PCA to identify sensitivity to the greatest data variance relating to the spectrum of soil health, multicollinearity of indicators measuring similar soil functions, and practicality of use. The reduced set of indicators include: water holding capacity, water-stable mega-aggregates, percent total organic carbon, C:N ratio, 24 hour CO_2 burst, β-glucosidase, β-glucosiminidase, hot water extractable organic carbon, and potentially mineralizable nitrogen. When management group averages were regressed on the gradient of observed soil health from PCA, these indicators behaved as expected to represent increasing soil health with shifts in management. To our knowledge, this study is the first to examine the sensitivities of soil health indicators in Hawaiʻi across soil order and land use and propose the best indicators of soil health across landscapes. Going forward, no one soil health test will universally function to predict soil health due to high variability among inherent soil properties across Hawaiian soil and goals of index use. The supplemental information of identifying soil health goals (e.g., crop production, forestry, grazing animal habitat) and soil taxonomy are crucial to utilize in the application of a soil health assessment tool, as well as soil fertility testing as needed within cropland systems.

Unlike soil taxonomy, there is freedom to adapt and change how a land is managed. Since land management is both a major driver of soil health and an aspect of the land that can be changed, there is incentive to prioritize soil health improvement by optimizing land use. Thriving soil life is at the apex of soil health and its recovery in these landscapes takes a considerable amount of time. Intensive agriculture across the majority of arable Hawaiian land has left the soil in a state of degradation even when left undisturbed for years or decades. While many land managers are prioritizing the improvement of their soil conditions, much of the previous intensive agricultural land is left unmanaged with only time to assist in the repair of abused soil. With the use of these identified indicators and an accepted initiative to improve soil health, the state of soil health in Hawaiʻi can be quantified and policy plans and incentive programs can be developed to protect the vitality of soil. Proper management of soil has the ability to reduce the expenses of crop production, support watershed recharge, mitigate climate change, and support food security in Hawaiʻi. The use of a soil health index is beneficial to all that rely on such functions of this precious natural resource. Further experiments from on-site farm trials of soil health management practices are necessary to continue the development of a soil health index using the proposed list of soil health indicators best suited for routine soil health testing in Hawaiʻi.

The health of soil in Hawaiʻi is not just the concern of land managers for the livelihoods of their businesses and organizations. Healthy soil supports effective watershed replenishment, clean air, food security, plant disease prevention, and so much more. To quote one land manager, *“Right now landscape degradation affects agriculture, but it’s truly everyone’s problem. It’ll become every resident’s concern when daily life is impacted, but then it may be too late.”*

The establishment of a soil health gradient primarily driven by land management supports the efforts of all natural resource managers in Hawai‘i, be it a rancher, a forest preserve manager, or a farmer. It shows opportunity for improvement and connects all land managers to a common goal of soil health. The preservation of Hawaiian landscapes is of imminent concern. The prioritization of Hawaiian soil as a vital natural resource depends on the collaboration of all types of land managers to improve soil health, as a common goal, for the short term benefits of their livelihoods as well as the long term benefits of generations to come.

APPENDIX A: SUPPLEMENTARY MATERIAL

A.1 Farmer perspectives and opinions on soil health

The development of resources for improving soil health in Hawaiʻi can be optimized by better understanding the needs of the audience. Soil health testing resource developers should know the opinions and interests of Hawaiʻi farmers regarding topics such as current and future participation in soil testing, and the process of soil management decision making. A series of survey questions was completed with eight participating land managers which was designed to explore the perspectives associated with soil testing use in Hawaiʻi, as well as collect information for future research in potential approaches for improvement. The land manager survey consisted of various sections in the form of multiple choice, mental mapping, Likert scales, and open response. Due to limited numbers in survey responses the reported information is not conclusive, however, it does provide insight to assist in further research on social perspectives of soil health in Hawaiʻi.

Survey contents

Fuzzy-logic Cognitive Mapping, originally developed by Kosko (1986), was utilized to develop an understanding of the relationships among farmer perceptions of soil health and management practices via mental modeling. This method quantifies the perceptions of farmers which can then be used to further understand soil health management decisions. The portion of survey used in mental mapping asked farmers about nine management practices that potentially impact soil health. The mental model tool visually displays the quantified farmer perceptions of each variable's impact (land management practice) on overall soil health and reports the 1) existence of a relationship, 2) if it is a positive or negative relationship and 3) the strength of relationship (Gray et al., 2014, Halbrendt et al., 2014). Participants also answered questions via a likert scale to quantify their opinions of soil health testing and resources in Hawai'i and were organized by average scores for each question regarding strength of agreement and then calculated as a total overall percent agreement for the group. Open responses were compiled and are reported as a summary of the information received. A total of seven surveys were completed.

Perspectives of soil health

The perceptions of the survey participants of the soil health suggest that these farmers are aware of what soil characteristics constitute a functional and healthy soil (Figure A.1). Management practices known to aggrade soil scored positive associations to soil health, while those known to degrade soil conditions scored negative. One practice, adding fertilizer, scored neutrally. These findings, provided a small size of participants, could suggest that education of soil management practices supporting soil health is not a main concern for improving soil health management with Hawaiian farmers. Rather, there are perhaps other conditions preventing such soil health management transitions such as lack of resources or labor. To improve this model, the sample size needs considerably greater participants as well as a follow up interview regarding what limits the use of sustainable agriculture practices.

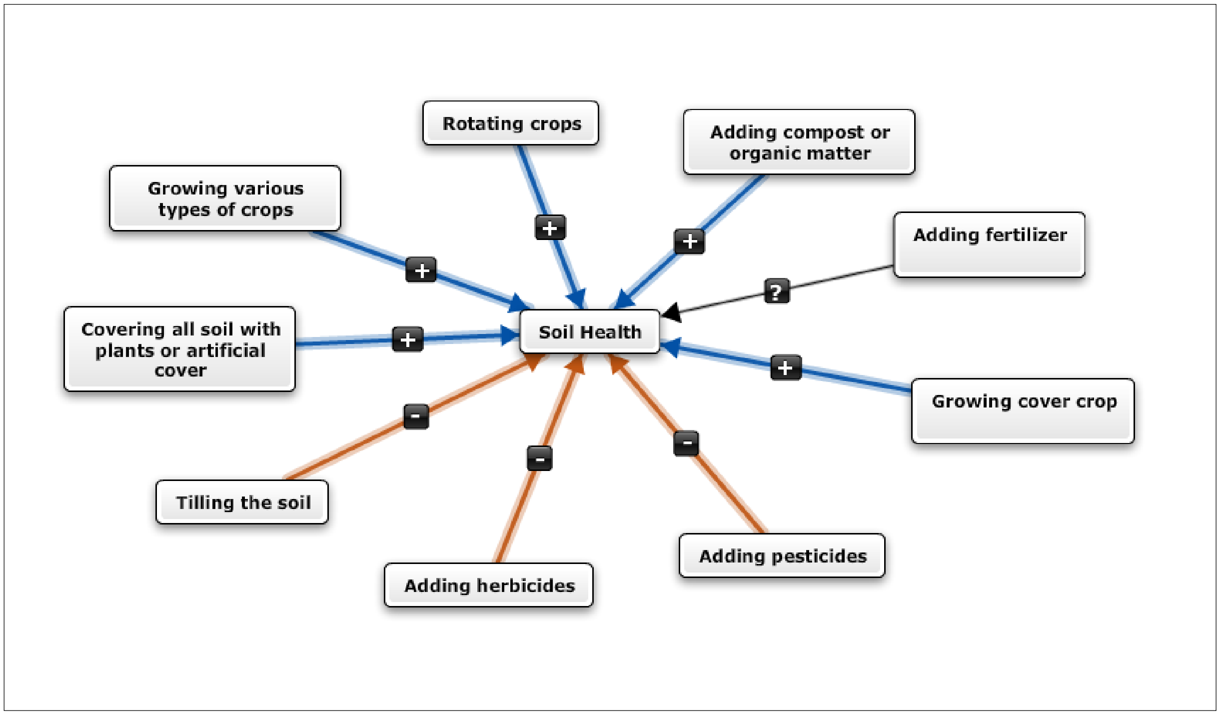


Figure A.1 Mental mapping of farmer perspectives on soil management practices impact on soil health. The existence of an arrow represents there is a relationship, which are then marked as positive or negative.

Opinions on soil management

Overall, farmers agreed soil health was important to them (97%) and soil testing is valuable (89%) as well as interest in adapting farm management practices to improve soil health, interest in testing soil health regularly, and interest in an online resource to help manage soil health (all 91%). Opportunities of improvement are: increasing the quality of resources available to farmers looking to improve soil management (74% of farmers agreed there is conflicting advice from soil health agencies/extension groups), and developing the scope of education and understanding of interdisciplinary potential of land uses regarding soil health (69% of farmers agreed agencies/extension groups concerned with soil health fail to understand landholder objectives). On average, the survey participants reported that $90 is a fair and reasonable price for a complete annual soil health test.

Conclusions

Improvement of resource quality available to Hawai‘i growers, such as where to find the most accurate soil health info online, how and when to test soil health, and who to consult for help with management changes, could be helpful steps in improving state sustainability. While most farmers surveyed appear to understand what constitutes a healthy soil, it appears they are lacking support to make changes. Recommended next steps to better connect and apply soil science with the Hawai‘i farmer audience are to develop and market reliable soil health testing, identify ways to better integrate farmer values into collaborating decision-making positions in science, government, and outreach personnel, and provide concise Hawai‘i-specific management strategies for improving soil health and plant disease.

APPENDIX B: MAPS

A.2 Areas of soil collection on Maui, Molokai, and Oahu with soil order overlay

Site marking symbols represent all sites in the general area, and are not specified to the detail of each exact site to protect the privacy of participating farmers.

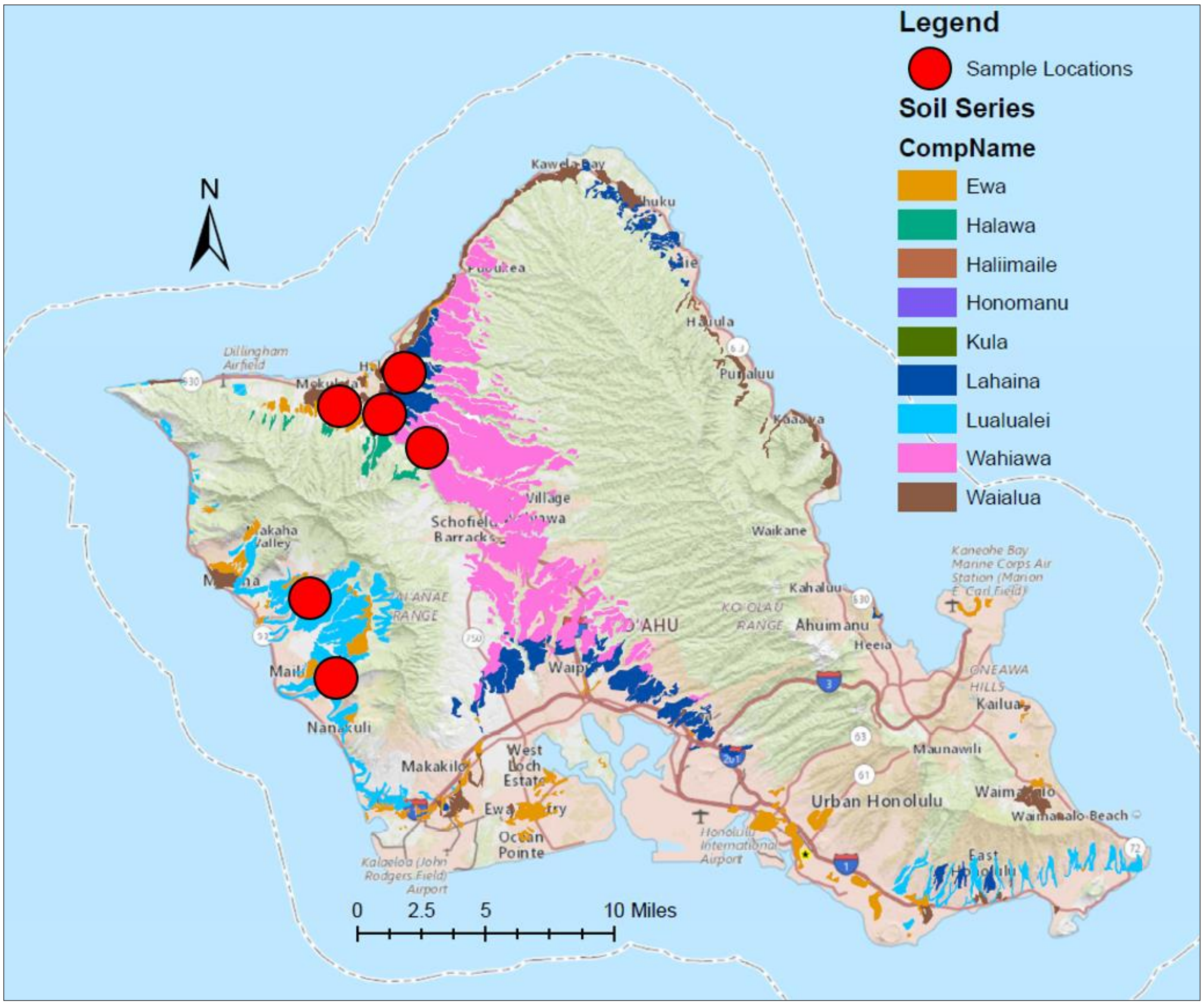


Figure A.2.a Map of sites on Oahu.

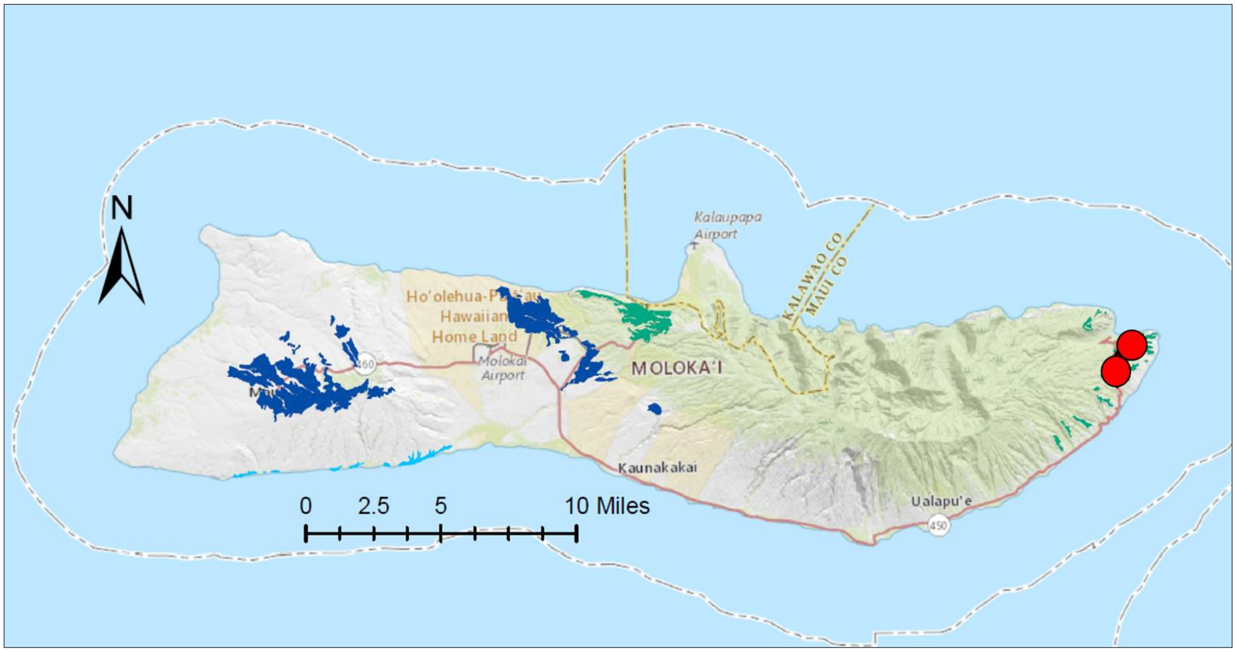


Figure A.2.b Map of sites on Molokai.

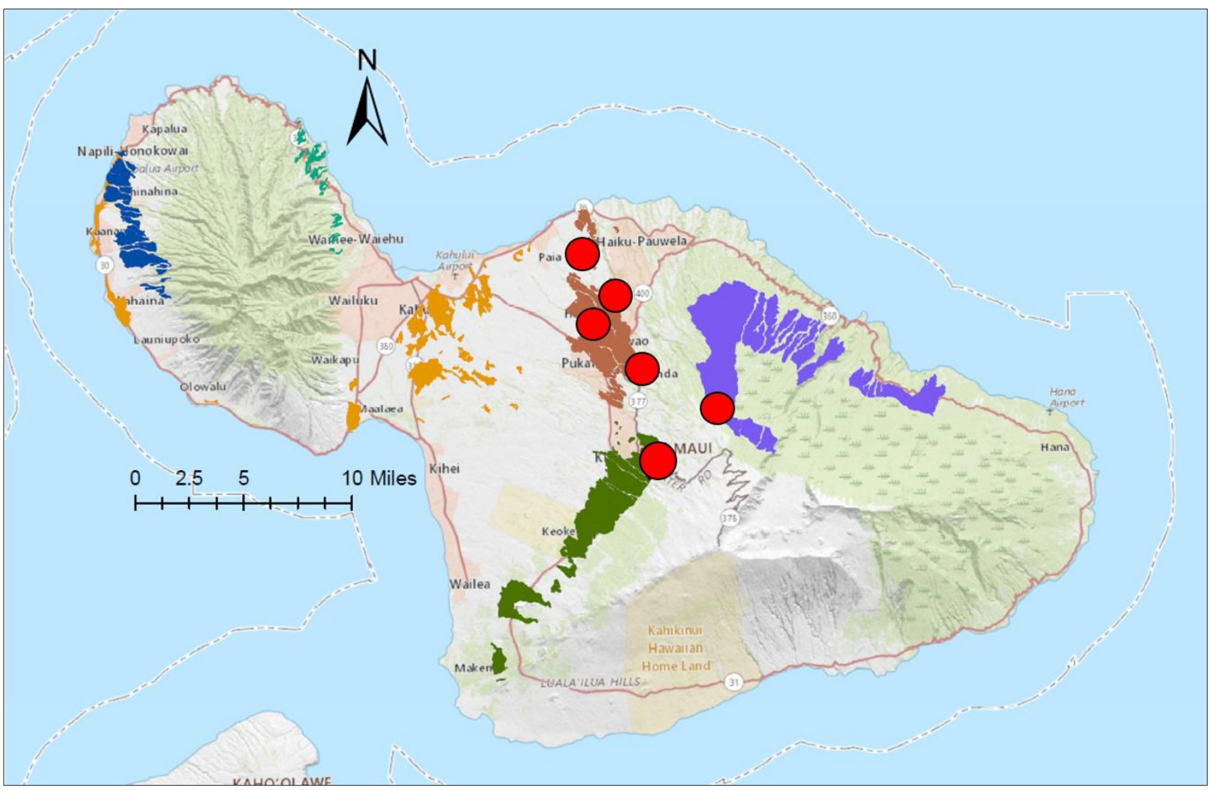


Figure A.2.c Map of sites on Maui.

A.3 Untransformed and transformed data in PCA for confirmation of non-normality

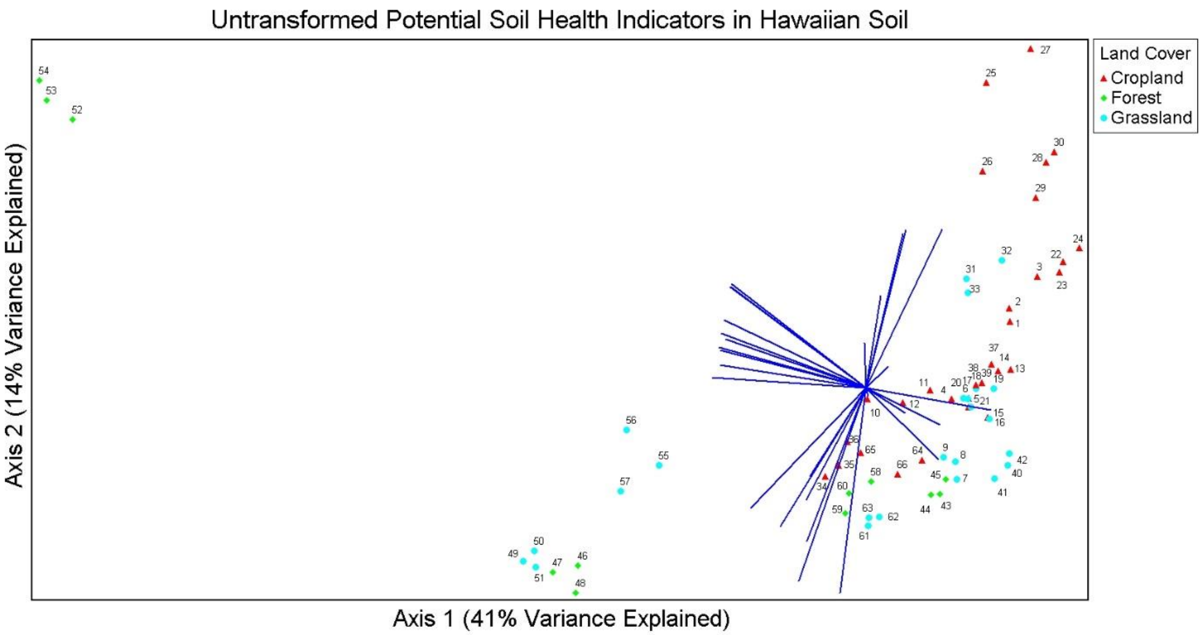


Figure A.3.a The initial PCA using untransformed data. The uneven distribution of data (with clear outliers 52-54) in the 2D output as well as high skewness values of some indicators suggested the need to transform data for normality.

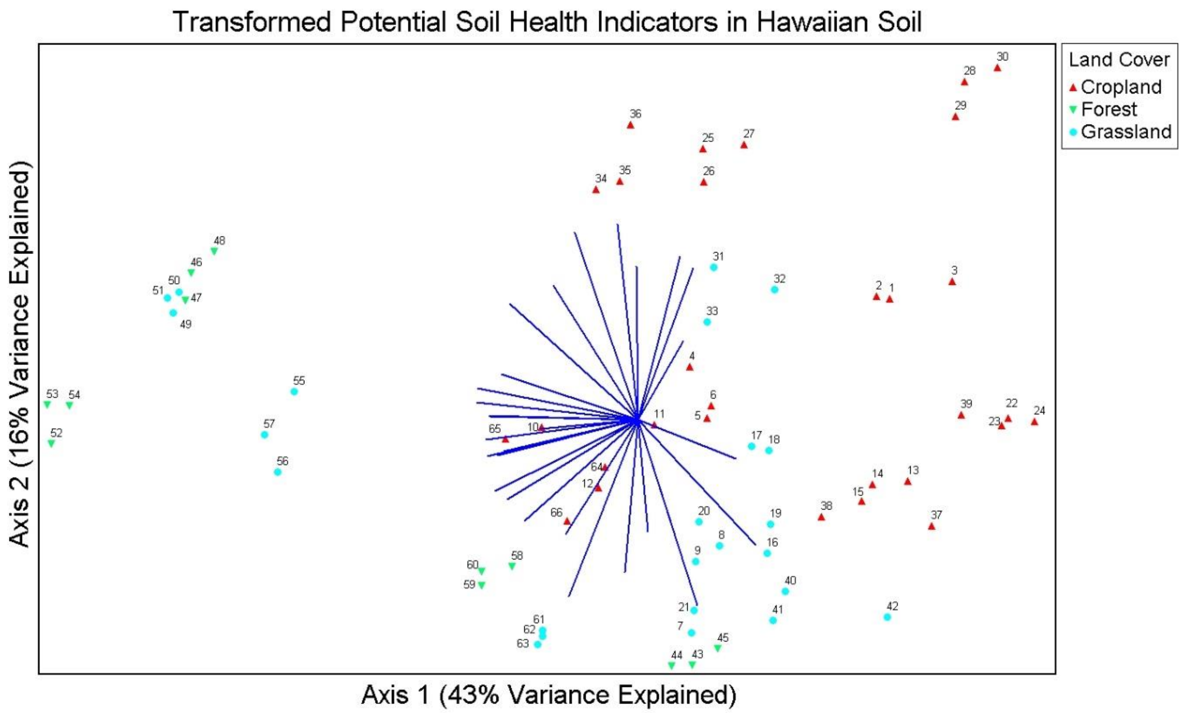


Figure A.3.b The final PCA using variables transformed for optimal normality which showed an improved graphical display regarding spatial distribution of plots and outlier assessment as well as reduced skewness values.

APPENDIX D: DATA SUMMARIES

A.4 Site data summaries with the proposed soil health indicators by soil order

Site parameter values are the average of the three pseudo field reps, with standard error in parentheses next to each value.

Table A.4.a Mollisol data for selected indicators.

MOLLISOLS

Soil Health Indicator	Units	Organic Cropland Waialua series Site A	Conventional Cropland Ewa series Site B	UPIAL Grassland Waialua series Site F
Total Organic Carbon	*(%)*	1.59 (0.05)	2.09 (0.02)	1.88 (0.03)
C:N	*Ratio*	9.97 (0.18)	10.19 (0.06)	11.47 (0.37)
Water Holding Capacity	*(Gravimetric, %)*	67.7 (0.76)	62 (0.8)	69.83 (0.75)
Water-stable Mega-aggregates	*(2-4mm, %)*	8.89 (2.76)	75.6 (0.47)	16.07 (1.75)
Hot Water Extractable Organic C	*(μg C/g soil)*	79.57 (23.53)	351.93 (6.85)	233 (7.98)
24 hr Soil Respiration	*(μg C/g soil)*	25.35 (1.52)	52.74 (1.06)	42.43 (1.3)
Beta-Glucosidsase	*(μg p-nitrophenol/g soil)*	55 (7.13)	83.72 (5.45)	148.53 (8.41)
Beta-Glucosiminidase	*(μg p-nitrophenol/g soil)*	12.55 (0.55)	17.1 (0.69)	30.62 (2.43)
Potentially Mineralizable N	*(μg N/g soil)*	0 (0)	12.73 (0.86)	16.73 (1.23)

Table A.4.b Oxisol data for selected indicators.

OXISOLS

Soil Health Indicator	Units	UPIAL Grassland Lahaina series Site C	Organic Cropland Lahaina series Site D	Conventional Cropland Lahaina series Site E	UPIAL Grassland Wahiawa series Site G	Conventional Cropland Wahiawa series Site H
Total Organic Carbon	*(%)*	1.97 (0.06)	3.25 (0.24)	1.35 (0.04)	2.01 (0.19)	0.89 (0.03)
C:N	*Ratio*	10.33 (0.15)	11.3 (0.1)	9.16 (0.11)	10.16 (0.13)	7.86 (0.27)
Water Holding Capacity	*(Gravimetric, %)*	66.47 (1.48)	76.07 (1.48)	65.23 (1.24)	69.13 (0.92)	69.3 (1.04)
Water-stable Mega-aggregates	*(2-4mm, %)*	47.06 (7.51)	40.49 (5.21)	5.97 (1.55)	71.83 (5.89)	2.68 (1.25)
Hot Water Extractable Organic C	*(μg C/g soil)*	292.7 (13.22)	563.27 (113.71)	145.63 (17.45)	311.3 (28.48)	176.1 (33.76)
24 hr Soil Respiration	*(μg C/g soil)*	50.14 (1.58)	116.73 (2.9)	24.91 (1.79)	86.83 (19.24)	43.65 (3.28)
Beta-Glucosidsase	*(μg p-nitrophenol/g soil)*	162.28 (23.14)	83.81 (17.33)	49 (1.94)	84.31 (9.01)	24.97 (1.7)
Beta-Glucosiminidase	*(μg p-nitrophenol/g soil)*	56.52 (1.8)	43.07 (3.36)	13.32 (2.07)	57.41 (8.91)	13.56 (2.61)
Potentially Mineralizable N	*(μg N/g soil)*	34.77 (1.68)	32.84 (1.9)	1.63 (0.87)	19.93 (2.6)	0 (0)

Table A.4.c Vertisol data for selected indicators.

VERTISOLS		Organic Cropland	Conventional Cropland	UPIAL Grassland
		Lualualei series	Lualualei series	Lualualei series
Soil Health Indicator	Units	Site I	Site J	Site K
Total Organic Carbon	*(%)*	1.93 (0.06)	0.83 (0.03)	2.58 (0.23)
C:N	*Ratio*	7.05 (0.11)	7.34 (0.3)	10.17 (0.4)
Water Holding Capacity	*(Gravimetric, %)*	91.1 (2.85)	84.3 (1.35)	73.07 (0.73)
Water-stable Mega-aggregates	*(2-4mm, %)*	0 (0)	0 (0)	10.82 (1.61)
Hot Water Extractable Organic C	*(µg C/g soil)*	461.87 (52.72)	113.23 (6.59)	391.17 (63.4)
24 hr Soil Respiration	*(µg C/g soil)*	59.82 (5.36)	13.25 (2.5)	39.66 (0.74)
Beta-Glucosidsase	*(µg p-nitrophenol/g soil)*	101.82 (13.81)	26.97 (1.78)	110.75 (10.04)
Beta-Glucosiminidase	*(µg p-nitrophenol/g soil)*	37.02 (1.81)	7.7 (1.3)	39.22 (3.74)
Potentially Mineralizable N	*(µg N/g soil)*	20.63 (3.9)	1.05 (0.59)	15.12 (2.02)

Table A.4.d Ultisol data for selected indicators.

ULTISOLS		Protected Non-native Forest	Pasture	Organic Cropland
		Halawa series	Halawa series	Halawa series
Soil Health Indicator	Units	Site T	Site U	Site V
Total Organic Carbon	*(%)*	5.31 (0.3)	3.84 (0.11)	5.61 (0.55)
C:N	*Ratio*	11.78 (0.21)	10.48 (0.08)	11.4 (0.34)
Water Holding Capacity	*(Gravimetric, %)*	69.03 (1.39)	56.73 (2.21)	69 (1.8)
Water-stable Mega-aggregates	*(2-4mm, %)*	85.42 (7.36)	91.82 (1.38)	68.93 (3.49)
Hot Water Extractable Organic C	*(µg C/g soil)*	723.53 (41.25)	551.87 (16.84)	760.47 (180.43)
24 hr Soil Respiration	*(µg C/g soil)*	130.59 (9.16)	89.63 (2.74)	76.2 (10.96)
Beta-Glucosidsase	*(µg p-nitrophenol/g soil)*	92.91 (13.4)	89.91 (13.35)	72.02 (9.56)
Beta-Glucosiminidase	*(µg p-nitrophenol/g soil)*	58.54 (4.46)	102.07 (12.59)	41.93 (1.52)
Potentially Mineralizable N	*(µg N/g soil)*	66.76 (4.27)	46.64 (2.6)	39.48 (1.7)

Table A.4.e Andisol data for selected indicators.

		ANDISOLS		
		Conventional Cropland	Protected Non-native Forest	Pasture
		Kula series	Kula series	Kula series
Soil Health Indicator	**Units**	**Site L**	**Site P**	**Site Q**
Total Organic Carbon	*(%)*	6.43 (0.21)	17.84 (0.6)	17.44 (0.27)
C:N	*Ratio*	10.57 (0.43)	15.6 (0.27)	12.51 (0.29)
Water Holding Capacity	*(Gravimetric, %)*	83.87 (6.56)	132.73 (7.51)	156.87 (1.37)
Water-stable Mega-aggregates	*(2-4mm, %)*	51.68 (5.86)	90.83 (1.21)	96.88 (0.53)
Hot Water Extractable Organic C	*(µg C/g soil)*	196.93 (32.68)	1611.4 (175.37)	1161.6 (202)
24 hr Soil Respiration	*(µg C/g soil)*	29.37 (1.03)	165.97 (31.01)	313.78 (14.56)
Beta-Glucosidsase	*(µg p-nitrophenol/g soil)*	63.93 (7.68)	181.21 (40.52)	230.54 (5.86)
Beta-Glucosiminidase	*(µg p-nitrophenol/g soil)*	18 (0.9)	134.04 (8.59)	108.02 (12.47)
Potentially Mineralizable N	*(µg N/g soil)*	5.59 (5.59)	86.71 (9.61)	82.87 (7.15)

Table A.4.f Inceptisol data for selected indicators.

		INCEPTISOLS				
		Conventional Cropland	Pasture	UPIAL Forest	Pasture	Protected Native Forest
		Haliimaile series	Haliimaile series	Haliimaile series	Haliimaile series	Amalu series
Soil Health Indicator	**Units**	**Site M**	**Site N**	**Site O**	**Site S**	**Site R**
Total Organic Carbon	*(%)*	1.13 (0.14)	1.95 (0.04)	2.57 (0.12)	11.09 (0.82)	32.45 (2.11)
C:N	*Ratio*	9.34 (0.61)	9.63 (0.15)	9.72 (0.08)	11.14 (0.48)	13.92 (0.24)
Water Holding Capacity	*(Gravimetric, %)*	67.5 (1.14)	61.63 (1.63)	58.33 (0.12)	116.2 (1.93)	208.47 (3.82)
Water-stable Mega-aggregates	*(2-4mm, %)*	10.67 (2.64)	42.11 (6.05)	86.23 (0.21)	88.6 (0.69)	43.45 (6.22)
Hot Water Extractable Organic C	*(µg C/g soil)*	48.37 (20.07)	121.77 (54.22)	257.8 (49.97)	2169.17 (73.06)	13400 (731.62)
24 hr Soil Respiration	*(µg C/g soil)*	19.12 (4.24)	30.36 (2.05)	41.33 (3.97)	277.38 (31.75)	527.05 (61.35)
Beta-Glucosidsase	*(µg p-nitrophenol/g soil)*	20.66 (6.29)	59.04 (9.49)	62.11 (9.28)	145 (59.87)	77.88 (18.22)
Beta-Glucosiminidase	*(µg p-nitrophenol/g soil)*	12.37 (4.91)	32.53 (3.16)	38.86 (5.97)	121.09 (11.01)	51.41 (4.31)
Potentially Mineralizable N	*(µg N/g soil)*	7.23 (1.99)	15.27 (0.95)	21.68 (1.02)	72.3 (2.1)	304.77 (59.97)

APPENDIX E: PCA ABBREVIATIONS

A.5 Soil parameter codes in PCA as potential indicators of soil health

Table A.5 A list of all potential indicators selected to be meaningful measurable parameters relating to an assessment of soil health for Hawaiʻi.

Soil Parameter Codes in PCA as Potential Indicators of Soil Health	
% Total Organic C	% C
% Total N	% N
C:N	C:N
pH	pH
% Sand	% Sand
% Silt	% Silt
% Clay	% Clay
Bulk Density	BD
Surface Hardness	Hardess@0
Hardness at 15cm	Hardess@15
Water Holding Capacity	WHC
% Water-stable mega-aggregates	%WSAmega
% Water-stable macro-aggregates	%WSAmacro
Total Dissolved Nitrogen	TDN
Potentially Mineralizable N	PMN
Extractable Calcium	Extract.Ca
Extractable Sodium	Extract.Na
Extractable Potassium	Extract.K
Extractable Phosphorus	Extract.P
Hot Water Extractable Inorganic N	HWEIN
Hot Water Extractable Organic C	HWEOC
Dissolved Organic C	DOC
Crystal-bound Fe	Crystal.Fe
Non-crystalline bound Fe/Al	Noncrystal.Al/Fe
% Total C Mineralized (Incubation)	%Cmin4mon
24 hr CO_2 burst	CO2 burst
Total PLFA	PLFA
Beta-glucosidase	Bgluc
Beta-glucosiminidase	BGlucmin
Acid phosphatase	AcidPhos

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