EXTENSION PUBLICATIONS

UNIVERSITY of HAWAI'I at MĀNOA
COLLEGE OF TROPICAL AGRICULTURE AND HUMAN RESILIENCE

What Is Soil Health in Hawai‘i?
(And How Do We Measure It?)

At a Glance: Soils and soil microbes play vital roles in the biogeochemical cycling of water and nutrients. Land management practices alter soil properties and impact the ability of soils to retain and release water and nutrients, filter pollutants, and sustain plant and animal life. Soil scientists in the University of Hawai‘i at Mānoa’s College of Tropical Agriculture and Human Resilience have identified 10 indicators that can be used to calculate a soil health score. By simplifying the comparison of soil management practices while accounting for differences in soil type, this Hawai‘i Soil Health Test can help growers and land managers improve soil health and function.

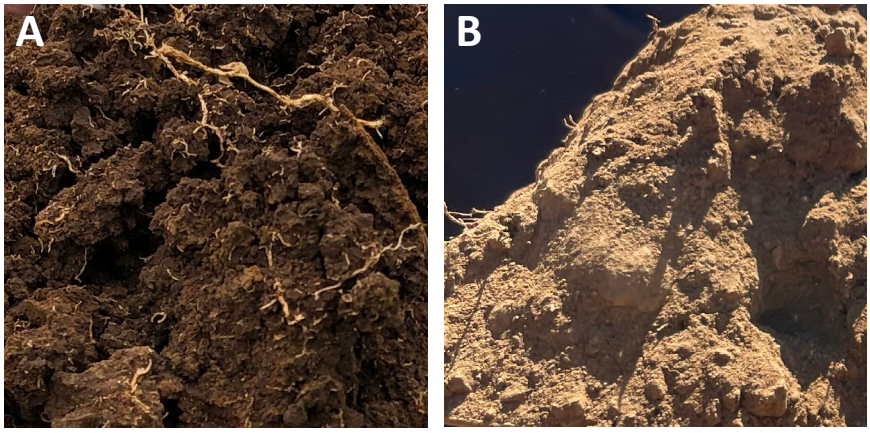

Figure 1. The effect of management on soil color and structure. **(A)** Soil sampled from a well-managed grazing land has strong structure, and its dark color signifies high levels of organic matter. **(B)** In contrast, the same soil type under conventional cropland has lost soil structure and is light in color as a result of the depletion of soil organic matter. Photos: Jonathan Deenik

Introduction

Soils provide critical functions that underpin both planetary and human health. They are primary habitat for a spectacularly diverse microbial world that drives essential nutrient cycles supporting plant growth and biodiversity. Microbially mediated biogeochemical cycles control soil organic matter dynamics, including carbon storage and greenhouse gas emissions. Soils are also a central feature of the hydrologic cycle governing water storage and purification. In direct support of human well-being, soils are responsible, directly or indirectly, for 95% of global food production (FAO 2015); provide fiber, fuel, and life-saving medicines (antibiotics); serve as an engineering medium for vital human infrastructure; and are an essential source of building materials (Kopittke et al. 2024).

Pre-contact Hawaiian agriculture comprised three primary systems: agroforestry, which relied on minimal disturbance and natural nutrient cycling; dryland cultivation, characterized by intensive mulching and fallow periods; and wetland systems (lo‘i), sustained through consistent green manuring (Handy and Handy 1972). These approaches, coupled with a deep spiritual connection to the land, maintained soil health and the capacity to support the population for more than a millennium.

Following the arrival of foreigners in the late 1700s, traditional land management was largely displaced by

October 2026

Subject Category: Soil and Crop Management, SCM-37

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plantation-scale sugarcane and pineapple production. This shift introduced intensive mechanization and a heavy reliance on synthetic inputs. Similar to other global regions, this intensification placed increasing stress on the soil, compromising its ability to perform critical ecological functions (Kopittke et al. 2019). Specifically, these intensive practices have depleted soil organic matter (SOM) by approximately 30–60% (Kopittke et al. 2017), significantly degrading the soil's long-term functional capacity. Land management practices that protect soil organic matter maintain a high level of soil health whereas management practices that deplete soil organic matter produce soils with low soil health (Figure 1).

As the long-term consequences of soil degradation have become evident through reduced productivity, greater input dependence, and increases in soil and water contamination, it has become clear that soil can no longer be managed solely as a growth medium for crops. This recognition has prompted the emergence of the soil health concept, which reframes soil as a living, dynamic system whose capacity to function depends on the integration of physical structure, chemical balance, and biological activity. A focus on soil health emphasizes management strategies that sustain and restore these functions rather than maximize short-term yields.

What Is Soil Health?

While indigenous farming practices have embodied soil stewardship and soil health principles for thousands of years across diverse regions of the world, these concepts were first introduced in the United States in the early 1900s by George Washington Carver, who advocated for crop rotations to address the negative effects of cotton monoculture in the Southern U.S. Also in the early 1900s, Sir Albert Howard began studying and documenting agricultural approaches in India; he wrote about the importance of implementing agricultural practices that respected and restored the health of the soil. Published the year of his death, *The Soil and Health: A Study of Organic Agriculture* (Howard 1947) summarized these principles for a general audience.

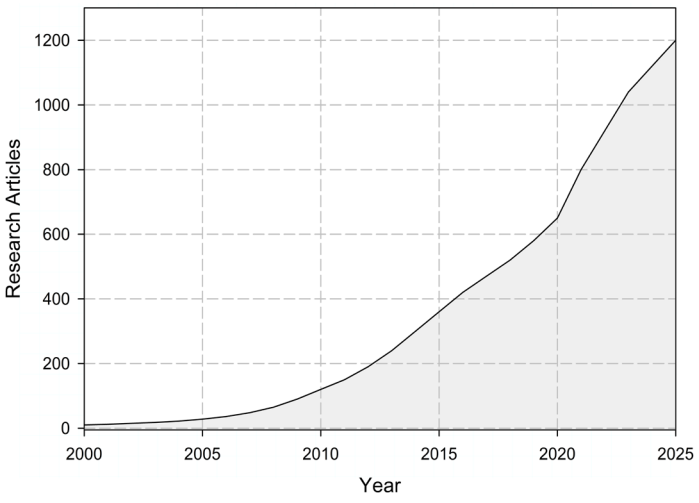

Figure 2. Trend in peer-reviewed soil health research articles from 2000–2025 showing exponential growth. Roughly half of the articles were published in the last five years. Data from a search in Web of Science, after Hou (2023).

Howard's writings inspired three important individuals—Lady Eve Balfour in England, and Jerome Rodale and Aldo Leopold in the United States—who each helped form the modern concept of soil health by tying the condition of the soil to broader ecological and human well-being. Balfour, in *The Living Soil* (1943) and through the Soil Association, argued that the health of soil, plants, animals, and people forms one interconnected system, emphasizing "living," biologically active soils maintained by organic matter and microbial life as the basis of long-term fertility. Rodale popularized the idea with the slogan "Healthy Soil = Healthy Food = Healthy People" and, through what became the Rodale Institute, promoted research and education on building healthy, living soils via organic methods, pushing soil health into public awareness and farmer practice. Leopold approached soil health through environmental ethics. In "The Land Ethic," published posthumously in *A Sand County Almanac* (1949), he framed land, including soils, as a biotic community whose "health" is measured by its integrity, stability, and beauty, warning that practices which deplete soil organic matter or fertility undermine the health of that whole community.

The 1990s brought about a focus on defining and measuring soil quality, which led to the formalization of the soil health concept in the 2000s and the rapid rise in research devoted to soil health. The U.S. Department of Agriculture's Natural Resources Conservation Service has embraced the soil health concept and promotes four key principles to manage soil for health (USDA NRCS n.d.):

- Maximize presence of living roots
- Minimize disturbance
- Maximize soil cover
- Maximize biodiversity

The dramatic expansion of soil health research (Figure 2) and the concomitant increased public interest in soil health has also given rise to many soil health definitions. The USDA definition is widely cited (USDA NRCS n.d.):

> *"Soil health is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Healthy soil gives us clean air and water, bountiful crops and forests, productive grazing lands, diverse wildlife, and beautiful landscapes."*

Per the USDA, soil does this by performing five essential functions (USDA NRCS n.d.):

- Regulating water
- Sustaining plant and animal life
- Filtering and buffering potential pollutants
- Cycling nutrients
- Providing physical stability and support

Many other definitions of soil health exist, but they all share the central concept of a living system characterized by biological, chemical, and physical properties that together provide key ecosystem services (Lehman et al. 2020). Janzen and his coauthors (2021) likened the soil health concept to a metaphor rather than a scientific construct. They argue that the quantification of soil health is just the first step in deepening our understanding of soil's importance and serves as a catalyst to improving soil management into the future.

Soil Health Indicators

The concept of soil health comprises the chemical, biological, and physical properties of soils that are associated with key ecosystem services (Figure 3). For example, pH is a chemical property of soil that governs nutrient availability and is directly linked to plant productivity; soil aggregate stability is a physical property associated with soil structure that controls water infiltration and percolation; and soil respiration is a biological property that is associated with microbial activity, organic matter decomposition, and nutrient cycling. Quantifying soil health begins with the selection of measurable indicators. These indicators are physical, biological, and chemical properties of soils that are dynamic and sensitive, changing in response to disturbances or stressors. Examples of soil health indicators include soil bulk density measurements (bulk density is affected by mechanized cultivation), soil respiration (an indicator of biological activity), and electrical conductivity (EC, an indicator of salinity that is sensitive to fertilizer inputs). Candidate soil health indicators should meet the following criteria (Lehman et al. 2020):

- Relevant to soil health and the various aspects of soil function
- Dynamic and sensitive to disturbance
- Cost-effective and feasible for routine laboratory analysis
- Interpretable for management decision-making

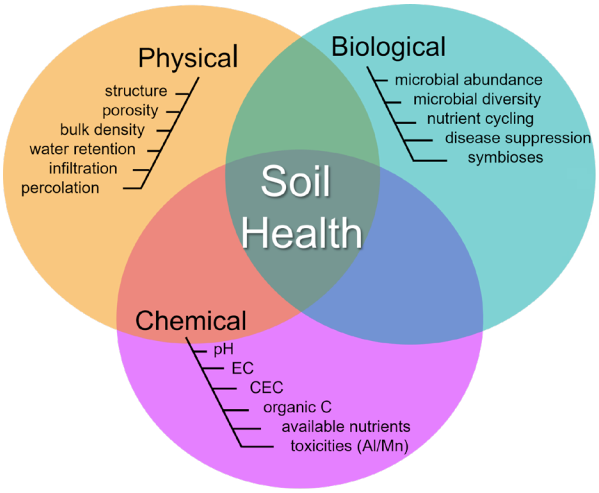

Figure 3. The three pillars of soil health: physical, chemical, and biological properties, with representative indicators for each category. EC: electrical conductivity; CEC: cation exchange capacity; Al: aluminum; Mn: manganese

A soil health test encompasses multiple indicators that adequately describe the physical, chemical, and biological properties of a soil related to soil function; the indicators must also show sensitivity to management practices. In other words, to be effective and useful, these indicators must show a response to changes in management and land use. As an example, Figure 4 shows that CO_2 burst (a measure of soil respiration) and water stable aggregates are two indicators related to biological and physical

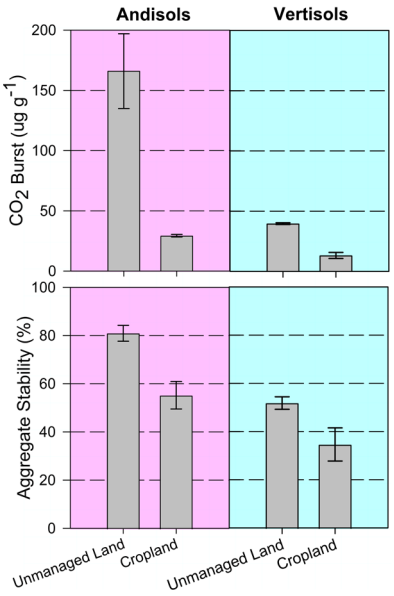

Figure 4. The negative effects of cultivation on CO_2 burst (a biological soil health indicator) and aggregate stability (a physical soil health indicator) in two important soil orders found in Hawai'i, Andisols (left-hand panels) and Vertisols (right-hand panels).

properties, respectively, that are sensitive to different management practices and land uses in two important agricultural soils of Hawai‘i (Table 1). The marked reduction in soil respiration and aggregate stability across both soil types demonstrates the negative impact of conventional tillage on microbial activity and physical structure. These declines, in turn, compromise microbially mediated functions like nutrient cycling as well as soil water dynamics, such as infiltration and percolation.

Beginning in 2015, our soil health team has conducted a study to identify appropriate soil health indicators for Hawai‘i’s diverse soil types and land uses (Crow et al. 2023). Three surface soil samples were collected at each of 22 sites covering six soil orders (Andisols, Inceptisols, Mollisols, Oxisols, Ultisols, and Vertisols; Table 1) and a range of land uses (forest, pasture, conventional cropland, and organic cropland). Each sample was analyzed for 46 parameters associated with soil health, of which 15 were biological, 22 were chemical, and 9 were physical properties. Through the application of robust multivariate and dimensionality-reduction statistical approaches, we identified a minimum dataset of 10 key soil health indicators that adequately characterized a soil’s health status and now serve as the foundation of the Hawai‘i Soil Health Test.

The Hawai‘i Soil Health Test

The current Hawai’i Soil Health Test consists of the 10 indicators outlined in Table 2. These were selected among 46 measured parameters for their connection to soil function, sensitivity to management, practicality lending to routine analysis, and cost-effectiveness. To be useful as a tool for management decision-making, a soil health test must integrate the individual indicators into a single soil health score reflecting the overall health and functionality of the soil. Such a score can then be used to guide management practices to achieve desired soil health goals. The score is based on an index that combines the 10 indicators into a single soil health variable through a defined statistical framework. After the selection of the minimum dataset of indicators, each indicator was transformed to a unitless score ranging from 0 to 1 using “more is better,” “less is better,” or “optimum” response curves. In the final step, a structural equation modeling approach was used to test which indicators were most strongly connected to soil health, quantify the strengths of each indicator path through regression, and define the indicator weights that resulted in a composite soil health score reflecting the inherent covariance structure of the data (Maaz et al. 2023).

Table 1. Characteristics of some soil orders in Hawai‘i

Soil Order	Description
Andisols	Soils formed primarily from volcanic ash or tephra, featuring an unusual low bulk density (light soils) and high water holding capacity. Andisols are dominated by poorly crystalline or amorphous clays with exceptionally high surface area that readily bind organic matter, resulting in high organic matter content. While they are generally fertile soils (except in areas with high rainfall), they strongly fix phosphorus into insoluble forms, requiring targeted management for agriculture.
Inceptisols	Generally immature soils without well-defined profile characteristics.
Mollisols	Fertile, nutrient-rich soils developed under grass vegetation. These soils are dominated by high activity clays and have good granular structure, making them prime agricultural soils.
Oxisols	Highly weathered, low fertility forest soils commonly found in the humid tropics. Intensive weathering and leaching have removed a large proportion of the silicate clays leaving behind low activity iron and aluminum oxide clays with very low nutrient retention capacity.
Ultisols	Ultisols in Hawai‘i are very similar to the Oxisols in properties and characteristics.
Vertisols	Vertisols are clay-rich soils dominated by expanding 2:1 smectite minerals that undergo dramatic shrink-swell cycles, creating deep surface cracks during dry seasons. While highly fertile these soils pose severe physical challenges for agriculture and infrastructure because they turn sticky and plastic when wet and become rock-hard when dry.

Adapted from Weil and Brady (2017)

Table 2. The 10 indicators comprising the Hawai'i Soil Health Test and their relationship to soil function

Indicator	Function	Score Impact	Soil Property
Total organic carbon (C) (%)	As the backbone of soil organic matter, a proxy measurement of the amount of soil organic matter. Soil organic matter influences physical, chemical, and biological processes in soil.	Higher is better.	Biological Chemical Physical
24 h CO_2 burst ($\mu g\ g^{-1}$)	Soil respiration in response to readily available substrate, a measure of overall microbial activity; a proxy for living organisms in soil.	Higher is better. (Higher means soil is more "alive.")	Biological
Potentially mineralizable nitrogen (N) ($\mu g\ g^{-1}$)	Potential of a soil to supply plant available nitrogen.	Higher is better. (Higher means soil can supply more plant-available N.)	Biological Chemical
ß-glucosidase (nmol g^{-1} soil h^{-1})	Enzyme responsible for initial breakdown of cellulose during organic matter decomposition.	Higher is better.	Biological
ß-glucosaminidase (nmol g^{-1} soil h^{-1})	Enzyme responsible for hydrolysis of chitin, plays key role in carbon and nitrogen cycling, related to N mineralization.	Higher is better.	Biological
pH	Nutrient availability and microbial composition.	Optimal range is better (5.5–7.0)	Chemical
Hot water extractable carbon ($\mu g\ g^{-1}$)	Readily available metabolic substrate; "food" for microbes.	Higher is better.	Chemical
Water stable mega-aggregates, 2–4 mm (%)	Water infiltration, porosity, aeration.	Higher is better.	Physical
Water holding capacity (%)	Plant–water relations.	Higher is better.	Physical
Bulk density ($g\ cm^{-3}$)	Infiltration, porosity, and rooting environment.	Lower is better.	Physical

Inherent soil properties—such as texture (sand, silt, clay) and clay mineralogy—must be explicitly considered in the development and interpretation of soil health tests, as they govern baseline soil behavior independently of management and land use, unlike the dynamic soil health indicators discussed above. In Hawai'i, where soils tend to be finely textured, clay mineralogy drives differences in soil behavior. Clay mineralogy is largely controlled by parent material and its age and weathering processes dependent on the interaction of precipitation gradients and topography.

Steep precipitation gradients and a varied topography have produced soils with widely varying clay mineralogy. For example, volcanic ash-derived soils on the younger islands of Hawai'i and East Maui are dominated by non-crystalline mineral clays (NCM) or amorphous clays with unique soil properties. By contrast, in soils on older islands with a wet climate, highly weathered aluminum-iron (Al-Fe) oxyhydroxide clays with low activity (LACs) dominate. Areas with drier climates or where drainage is restricted have soils higher in high activity clays (HACs). In this context, activity refers to the clay's ability to hold or exchange plant nutrients and its tendency to shrink and swell. LACs have a limited capacity to hold nutrients and a low shrink-swell potential, and HACs are high in nutrient retention and shrink-swell potential.

Differences in clay mineralogy strongly influence a soil's physical, chemical, and biological behavior through their effects on surface area, charge characteristics, total porosity, aggregation, microbial habitat, and the stabilization of soil organic matter. In Figure 5A, we see that bulk density varies significantly (P<0.001) depending on clay type, with soils rich in amorphous clays (e.g., allophane, imogolite, and ferrihydrite) showing much lower bulk densities than soils with crystalline clays (HACs and LACs). We also see that soils enriched in amorphous clays contain the highest concentrations of organic carbon (Figure 5B). The high amounts of organic carbon in these soils is a function of high surface area, high reactivity, and the strong aggregating properties of amorphous clays that work together to protect carbon chemically and physically. We also see that clay mineralogy has a strong effect on surface charge, with soils rich in HACs possessing much higher cation exchange capacity than LAC-rich soils (Figure 5C). These intrinsic mineralogical differences confer inherent properties to soils that must be addressed separately from the effects of management. By explicitly accounting for clay mineralogy and its effects on inherent soil properties, soil health testing can provide meaningful, comparable, and actionable evaluations of soil health across diverse soils.

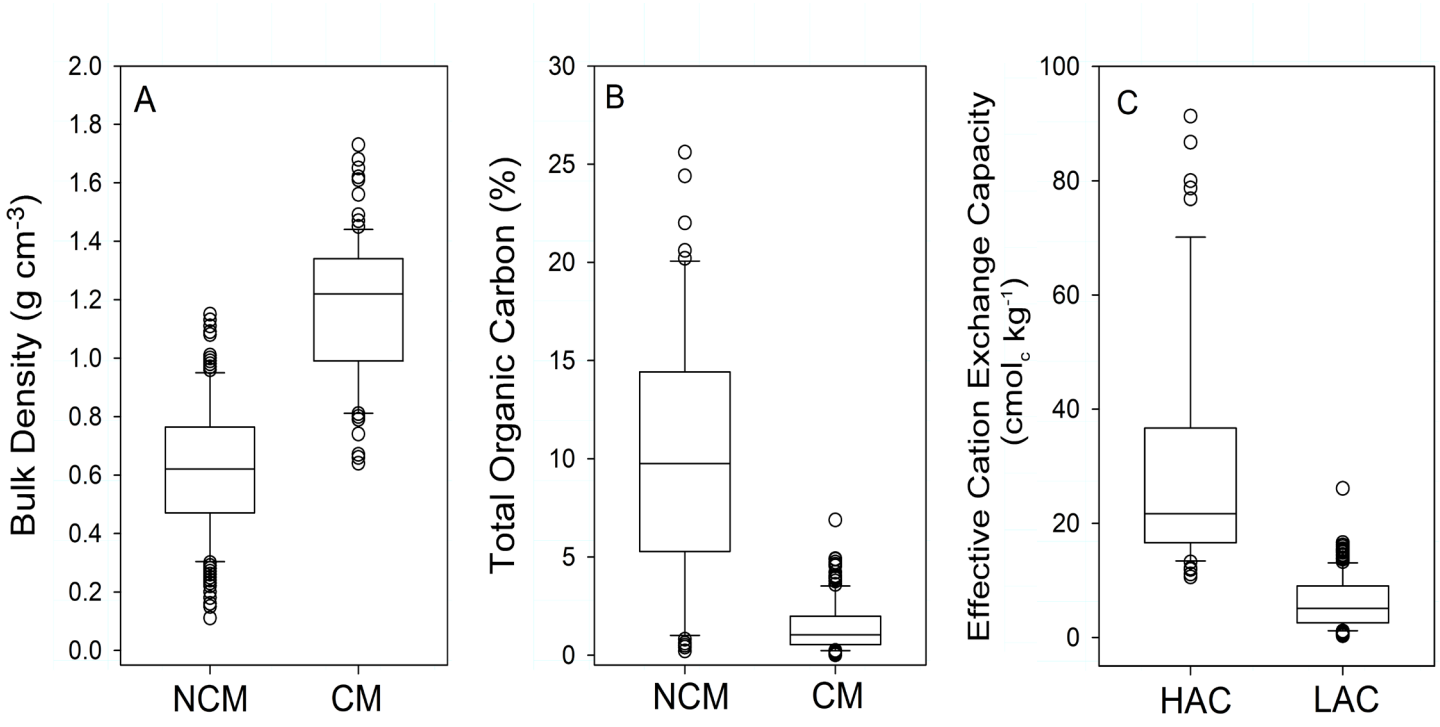

Figure 5. Box and whisker plots showing the inherent effects of clay mineralogy on **(A)** soil bulk density, **(B)** total organic carbon, and **(C)** effective cation exchange capacity. **(A,B)** Soils dominated by amorphous and non-crystalline clays (NCM) show distinct differences in bulk density and total organic carbon compared with soils with crystalline clay minerals (CM). **(C)** Soils with high activity clays (HAC) have a higher cation exchange capacity than soils with low activity clays (LAC).

The Hawai'i Soil Health Test modeling framework explicitly adjusts soil health indicator values for clay mineralogy to ensure that the resulting soil health scores reflect contemporary management rather than inherent differences in clay mineralogy. This adjustment prevents soils from being unfairly penalized or advantaged due to their mineralogical class when comparing soil health scores across diverse soils and land uses.

Using the Hawai'i Soil Health Test

An effective soil test must be able to correctly diagnose a condition. For example, we might ask how land use affects soil health? When we apply the Hawai'i Soil Health Test to over 1,800 samples collected from various land uses, we see that the test is able to differentiate land use effects on soil health (Figure 6). As we might have expected, croplands showed the lowest mean score, which reflects the negative effects of high disturbance associated with intensive agriculture.

A closer examination of Figure 6 shows substantial variability in soil health scores in the cropland category, prompting the question whether this variability is driven by management type (organic versus conventional). When we compared the two management approaches (Figure 7), we found that soil health scores in the organically managed croplands (mean value 0.51) were about two-fold higher than the scores in the conventionally managed soils (mean value 0.25). The higher soil health scores observed in organically managed soils are expected, as organic agriculture promotes the accumulation of soil organic matter, thereby enhancing indicators of substrate availability and microbial activity, including total organic carbon, hot-water extractable carbon, CO_2 burst, and potentially mineralizable nitrogen.

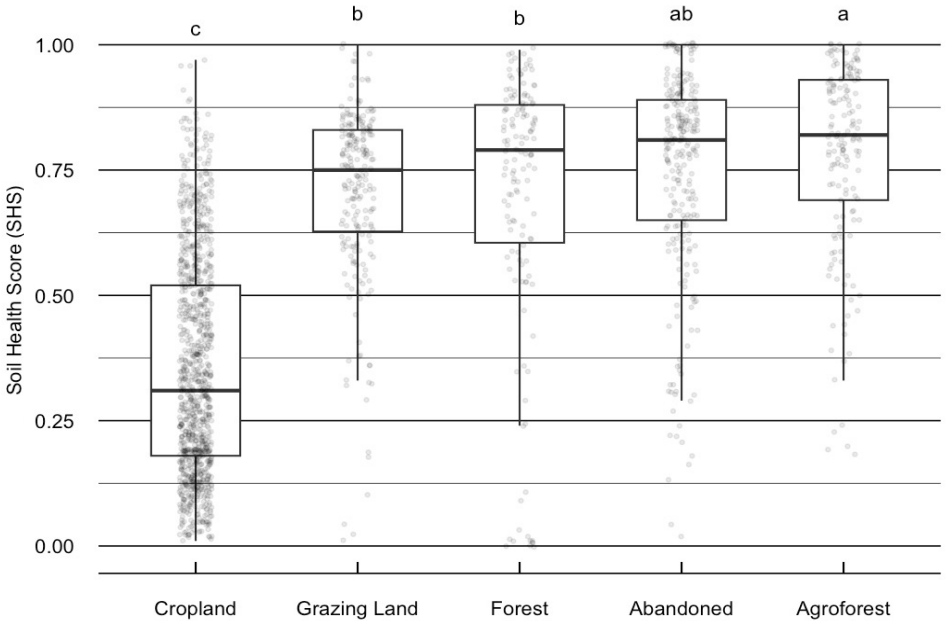

Figure 6. Box and whisker plot showing land use effects on soil health scores. The mean for each category is denoted by the horizontal line within each box. Categories with the same letter are not statistically different from each other (P<0.05). The data come from the Hawai'i Soil Health Database.

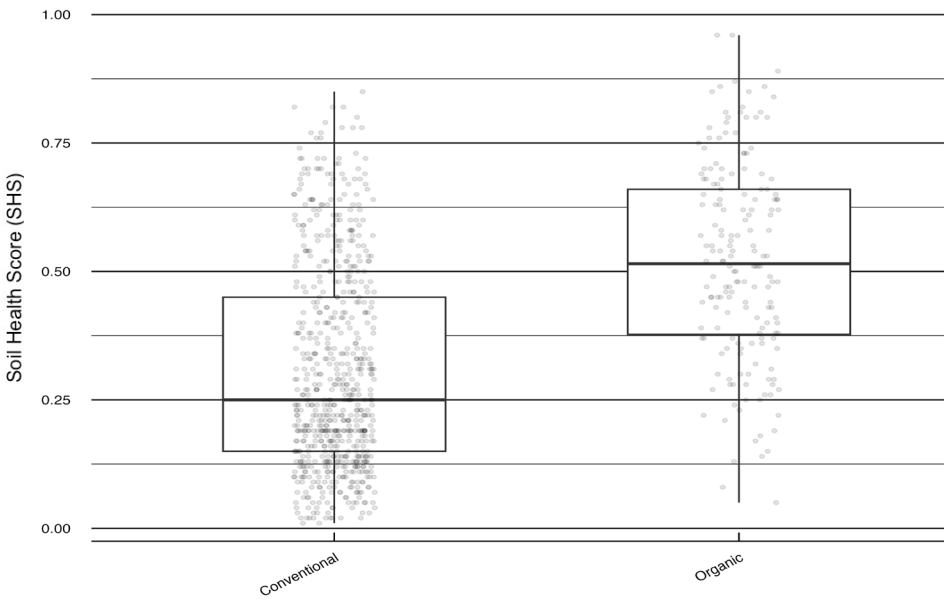

Figure 7. Box and whisker plot showing the effect of conventional versus organic management practices on soil health scores. The mean for each category is denoted by the horizontal line within each box. The data come from the Hawai'i Soil Health Database (N=679 for conventional and N=206 for organic).

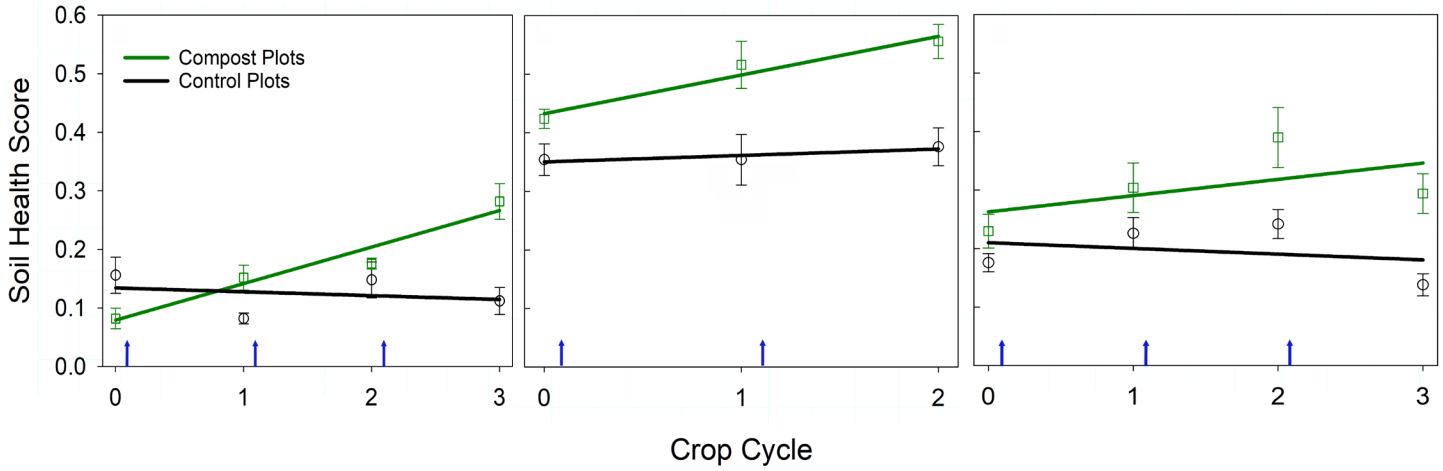

Figure 8. Soil health score responses to compost applications at three commercial farms on O'ahu. Treatment plots (in green) were amended with compost, which was applied at the equivalent of 20 tons per acre prior to each crop cycle; no compost was applied to the control plots (in black). The dark blue arrows indicate times of compost application. Each point is a mean of five soil samples.

In addition to differentiating land use effects on soil health, an effective soil health test should reliably detect soil health responses to on-farm changes in soil management. Using on-farm trials supported by the NRCS Conservation Innovation Grant program, we used the Hawai'i Soil Health Test to monitor the impacts of soil health-building management practices over three years. We monitored soil health responses to annual applications of compost at three different farms (Figure 8). At all three sites, compost increased soil health scores compared with the control plots that received no compost. We note that the soil health score trajectories in the compost plots were always positive whereas the control plots showed a slight negative trajectory at two sites.

Conclusion

Soil health is a topic of increasing interest among producers and the general public. Understanding soil health is essential, because soils are not static media for growing plants, but instead are living systems that support crop production, water regulation, nutrient cycling, and long-term ecosystem resilience. A soil health test helps make these complex functions visible and measurable, giving growers and land managers a clearer picture of how their soils are functioning and how management decisions affect soils over time.

The Hawai'i Soil Health Test provides a practical decision-making tool that can identify strengths and limitations in the physical, chemical, and biological properties of soil, track changes in these properties in response to management, and guide more effective practices that build soil function and resilience. By accounting for dynamic indicators as well as inherent soil properties, the test offers a more meaningful and fair assessment of soil condition across different fields and land uses, helping farmers and land managers make informed choices that support both current goals and long-term soil stewardship.

Acknowledgements

This publication represents a collaborative effort between the agricultural community, academic researchers, and extension agents. Our deepest thanks go to the participating farmers for opening their fields to us and sharing their foundational knowledge. Special thanks to the Soil (Health, Environment, and Ecosystem) Resilience Lab—the S(HEE)R Lab—at the University of Hawai'i at Mānoa for their soil sample analysis that made these insights possible. Funding for this effort was provided by the United States Department of Agriculture, Conservation Innovation Program award #NR213A750013G011.

References

Balfour, E.B. 1943. The Living Soil: Evidence of the importance to human health of soil vitality, with special reference to post-war planning. London: Faber and Faber. 270 pp.

Crow, S.E., H. Hubanks, J.L. Deenik, T.M. Maaz, C. Tallamy Glazer, E. Vizka, and J. Rivera-Zapas. 2023. The legacy of intensive agricultural history on the soil health of (sub) tropical landscapes. Frontiers in Environmental Science 10:991262. https://doi.org/10.3389/fenvs.2022.991262

FAO (Food and Agriculture Organization of the United Nations). 2015. Healthy soils are the basis for healthy food production. I4405E/1/02.15. Accessed July 2, 2026,

from **https://openknowledge.fao.org/server/api/core/bitstreams/4fb89216-b131-4809-bbed-b91850738fa1/content**

Handy, E.S.C., and E.G. Handy (with the collaboration of M.K. Pukui). 1972. Native Planters in Old Hawaii: Their Life, Lore, and Environment. Bernice P. Bishop Museum Bulletin 233. Honolulu: Bishop Museum Press. **https://files.hawaii.gov/dlnr/ld/CCH-LD-01/exhibits/Plaintiff%20Sierra%20Clubs%20Exhibits/87%20Handy%20&%20Handy.pdf**

Howard, A. 1947. The Soil and Health: A Study of Organic Agriculture. New York: The Devin-Adair Company. 320 pp.

Hou, D. 2023, Soil health and ecosystem services. Soil Use and Management 39:1259–1266. **https://doi.org/10.1111/sum.12945**

Janzen, H.H., D.W. Janzen, and E.G. Gregorich. 2021. The 'soil health' metaphor: Illuminating or illusory? Soil Biology and Biochemistry 159:108167. **https://doi.org/10.1016/j.soilbio.2021.108167**

Kopittke, P.M., R.C. Dalal, D. Finn, and N.W. Menzies. 2017. Global changes in soil stocks of carbon, nitrogen, phosphorus, and sulphur as influenced by long-term agricultural production. Global Change Biology 23:2509–2519. **https://onlinelibrary.wiley.com/doi/10.1111/gcb.13513**

Kopittke, P.M., N.W. Menzies, P. Wang, B.A. McKenna, and E. Lombi. 2019. Soil and the intensification of agriculture for global food security. Environment International 132:105078. **https://doi.org/10.1016/j.envint.2019.105078**

Kopittke, P.M., B. Minasny, E. Pendall, C. Rumpel, and B.A. McKenna. 2024. Healthy soil for healthy humans and a healthy planet. Critical Reviews in Environmental Science and Technology 54(3):210–221. **https://www.tandfonline.com/doi/full/10.1080/10643389.2023.2228651#abstract**

Lehmann, J., D.A. Bossio, I. Kögel-Knabner, and M.C. Rillig. 2020. The Concept and Future Prospects of Soil Health. Nature Reviews Earth & Environment 1(10):544–553. **https://doi.org/10.1038/s43017-020-0080-8**

Leopold, A. 1949. A Sand County Almanac and Sketches Here and There. New York: Oxford University Press. 226 pp.

Maaz, T.M., R.H. Heck, C. Tallamy Glazer, M.K. Loo, J. Rivera Zayas, A. Krenz, T. Beckstrom, S.E. Crow, and J.L. Deenik. 2023. Measuring the Immeasurable: A Structural Equation Modeling Approach to Assessing Soil Health. Science of the Total Environment 870:1–12. **https://doi.org/10.1016/j.scitotenv.2023.161900**

USDA NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service). n.d. Soil Health. Accessed July 2, 2026, from **https://www.nrcs.usda.gov/conservation-basics/soil/soil-health**

Weil, R.R., and N.C. Brady. 2017. The Nature and Properties of Soils, 15th ed. New York: Pearson. 1,104 pp.

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