

# What We Talk about When We Talk about Soil Health

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### Core Ideas

- Despite nationwide emphasis on soil health in the USA, current measurements lack consistency.
- A meta-analysis showed 8 of 42 soil health indicators reported >20% of time.
- Only 13 indicators showed short-term (1–3 yr timescale) responses to cover cropping.
- Wide variation in soil sampling protocols suggests standardization is needed.
- Translating soil health research across systems requires a common framework.

**Abstract:** Despite a nationwide emphasis on improving soil health in the United States, current measurement protocols have little consistency. To survey assessment practices, we conducted a meta-analysis of cover crop ( $n = 86$ ) and no-tillage ( $n = 106$ ) studies and compiled reported indicators, cropping systems, and soil sampling protocols from each. We then analyzed which indicators significantly responded to cover crop usage after 1 yr and 2 to 3 yr. Our results showed that out of 42 indicators, only 8 were reported in >20% of studies. Thirteen indicators showed >10% relative response after 1 to 3 yr; the remainder lacked either sufficient observations or consistent results. Looking forward, we propose that emphasis should be placed on (i) pursuing dynamic indicators (e.g., aggregate stability), (ii) standardizing sampling protocols, and (iii) developing a common framework for information sharing. These efforts will generate new insight into soil health across systems, ultimately ensuring that soil health science is useful to producers and regulators.

AS THE International Decade of Soils (2015–2024) draws to its midpoint, the importance of soils is being recognized, from mainstream media articles (Velasquez-Manoff, 2018) to global climate modeling efforts (Or et al., 2018). Conservation agencies such as the USDA Natural Resources Conservation Service (NRCS) have made soil health—i.e., the maintenance of soil ecology and properties aimed at sustaining plants, animals, and humans (USDA–NRCS, 2018)—a primary focus of outreach and research efforts. Enterprises such as the Soil Health Partnership and the Soil Health Institute have emerged from this renewed focus on soil management and quality. At the university level, initiatives such as the Cornell Comprehensive Assessment of Soil Health have focused on the collection of soil health measurements. These entities support widespread implementation and research activities, with the goal of improving soil health across the United States and around the world.

Despite building on decades of prior inquiry, research efforts on quantifying and interpreting parameters that would define soil health often take a scattershot approach, with each study focused on a handful of indicators and how they respond to one or two interventions. Such haphazard approaches have led to equivocal conclusions. For example, no-till sometimes enhances infiltration rates (Haruna et al., 2018) yet sometimes does not (Blanco-Canqui et al., 2017). There is also increasing concern that many current soil health metrics lack sufficient sensitivity to resolve differences from management practices (Roper et al., 2017) and that certain indicators have excessive inter-laboratory variability (Wade et al., 2018).

In response, efforts are underway to standardize and compile soil health studies. The Soil Health Institute has endorsed 19 “Tier 1” indicators (Indicators 1–19 in Fig. 1) that include some, but not all, of the measurements provided by the USDA–NRCS Soil Quality Test Kit (USDA, 1999). Notable omissions include soil respiration, slaking, and earthworm tests. The Tier 1 list also does not include any biological components, the Soil Health Institute instead relegating indicators such as  $\beta$ -glucosidase to Tier 2 status (“Soil Health Indicators

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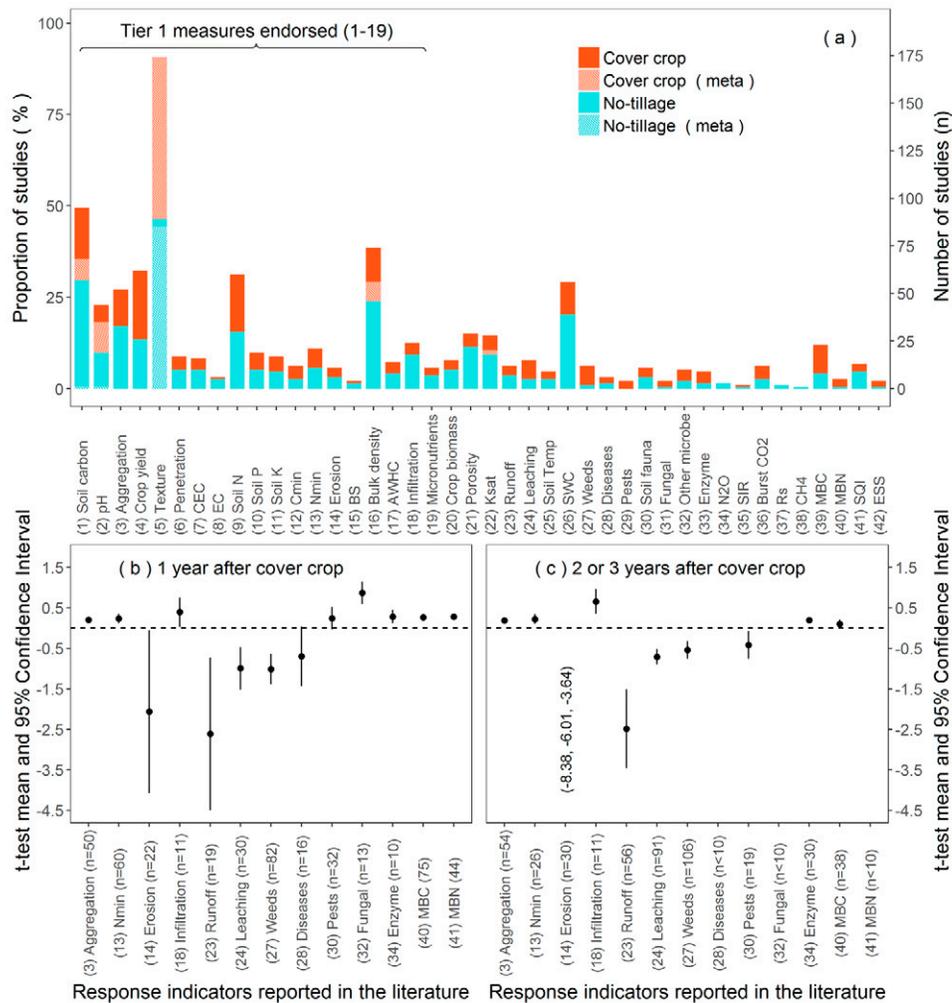
Supplemental material is available online for this article.

Agric. Environ. Lett. 3:180033 (2018)  
doi:10.2134/ael2018.06.0033

Received 26 June 2018.

Accepted 5 Oct. 2018.

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**Fig. 1.** (a) Response indicators and the number of studies reporting each indicator from 86 cover crop and 106 no-tillage studies. Indicators include (1) soil C, (2) pH, (3) aggregation, (4) crop yield, (5) texture, (6) penetration resistance, (7) cation exchange capacity, (8) electricity conductivity, (9) soil N, (10) soil P, (11) soil K, (12) mineralizable C, (13) mineralizable N, (14) soil erosion, (15) base saturation, (16) bulk density, (17) available water holding capacity, (18) infiltration, (19) micron C, (20) total cash crop biomass, (21) porosity, (22) saturated conductivity, (23) runoff, (24) nutrient leaching, (25) soil temperature, (26) soil water content, (27) weed control, (28) diseases, (29) pests, (30) soil fauna, (31) fungal indicators, (32) other microbial indicators, (33) enzymatic assays, specifically,  $\beta$ -glucosidase activity and phenol oxidase, (34) soil  $N_2O$  emissions, (35) SIR (substrate-induced respiration), (36)  $CO_2$  burst test, (37) Rs (soil respiration), (38) soil  $CH_4$  (methane) emissions, (39) microbial biomass C, (40) microbial biomass N, (41) soil quality indicators, and (42) ecosystem services. Indicators 1–19 represent Tier 1 measurements endorsed by the Soil Health Institute, and indicators identified as (meta) were reported as meta-data within the site descriptions, rather than as data used to evaluate experimental treatments. Panels (b) and (c) present  $t$  test results for indicators that were measured in cover cropping studies after (b) 1 and (c) 2–3 yr; response was quantified as  $\ln[\text{cover crop}/\text{control}]$ , and only indicators in which the  $t$  test mean response was  $\geq 0.1$  or  $\leq -0.1$  are shown.

and Methods to be Assessed”). This apparent lag in incorporating biological indicators into soil health assessments highlights the need for the soil health community (e.g., scientists, regulators, agency personnel) to focus on evaluating and refining these metrics.

The Soil Health Institute has also developed a Research Landscape Tool that compiles soil health results into a searchable database, linking problems to outcomes (Soil Health Institute, 2016). Likewise, the Soil Health Partnership (<https://www.soilhealthpartnership.org/>), a regional program from the National Corn Growers Association, has created a database from their grower network. As a result, soil health now has substantial momentum for defining management strategies and research efforts. This momentum provides new opportunities but also increases the risk that

interest and funding will wane without tangible soil health improvements. To avoid such an outcome, our purpose here is to provide a survey of what is currently measured related to soil health, discuss how method standardization could be improved, and consider how a common framework could advance the science and practice of soil health.

## What Do We Measure When We Measure Soil Health?

The NRCS lists four soil health planning principles: (i) minimizing disturbance, (ii) maximizing biodiversity, (iii) maximizing soil cover, and (iv) maximizing living roots (USDA–NRCS, 2018). These principles inform the four main actions of the Soil Health Institute Research Landscape Tool;

therefore, we compiled all papers listed at the Soil Health Institute under “Residue and Tillage Management, No-Till” and “Cover Crop” (approximately half of the total references in the Research Landscape Tool; Supplemental Table S1). Altogether, we found 106 peer-reviewed studies listed under no-till and 86 under cover crops, totaling 192 unique peer-reviewed studies. We recorded all meta-data (e.g., crop rotation) and the type and number of soil health measurements reported. A listing of all papers reviewed in this effort are provided in the supplemental material (Supplemental Tables S1 and S2).

The 192 studies occurred throughout North America, although most (~70%) were located in the South and Midwest census regions of the United States (Fig. 2). As detailed in the supplemental material, the earliest study occurred in 1943; the most recent studies came from 2015. Cover crop and no-tillage studies both reported an average of four soil health indicators. Over the past four decades, the mean number of indicators measured in cover crop studies did not change, but it significantly increased for no-tillage research ( $p < 0.05$ ). Of all studies, 55% used cash crop monocultures; only 10% of studies rotated three or more cash crops. Most cover crop studies used either a single grass or legume species as the cover crop, with cereal rye (*Secale cereale* L.) used in 20% of studies. Only 10% of studies examined cover crop mixtures, indicating comparatively little focus on soil health effects of multispecies mixtures despite their potential benefits (Chu et al., 2017). In terms of soil sampling, 60% of studies reported results for only one depth increment. In 30% of studies, the surface sample included only the upper 5 cm of soil, while in 20% of studies the surface sample extended to a depth  $\geq 30$

cm. These results signify substantial variation in sampling protocols for assessing soil health.

We grouped all measurements into 42 indicators, of which only 8 were reported in  $>20\%$  of studies (Fig. 1a). Soil texture was most commonly reported (85% of studies). However, all but three of those studies reported texture as meta-data within general site descriptions (i.e., studies labeled “meta” in Fig. 1a), rather than as data used to evaluate experimental treatments. Soil carbon (50% of studies, with 15% reporting as meta-data) and bulk density (40% of studies, with 10% reporting as meta-data) were also commonly reported, with values listed more often in no-tillage studies than cover crop studies. Crop yield, despite being of paramount interest to farmers, was recorded in less than one-third of all studies.

We also analyzed the responsiveness of each indicator to cover crop treatments using a  $t$  test, with the response ratio ( $R_r$ ) of each observation quantified as  $R_r = \ln[\text{cover crop}/\text{control}]$ . Only indicators that had  $n \geq 10$  observations from 1 yr or 2 to 3 yr after cover crop implementation were included. After 1 yr, 13 of the 42 indicators showed  $|R_r| \geq 0.10$  (equal to a 10% relative change; Fig. 1b). After 2 to 3 yr, 10 of the indicators showed  $|R_r| \geq 0.10$  (Fig. 1c). The remaining indicators either had negligible response or lacked sufficient observations to analyze ( $n < 10$ ).

## What Should We Measure When We Measure Soil Health?

The 42 indicators can be grouped into six categories: physical properties (Indicators 3, 5, 6, 16–18, 21, and 22 in Fig. 1a), chemical characteristics (Indicators 1, 2, 7–11, 15, and

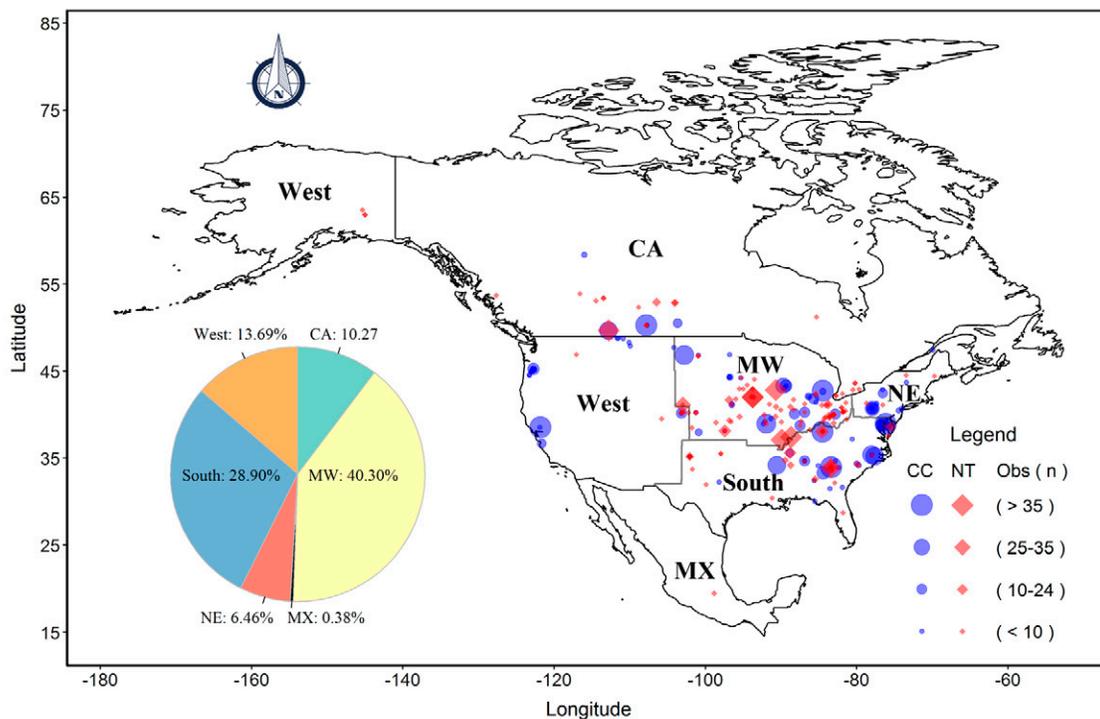


Fig. 2. The spatial distribution of sites from 86 cover crop (CC) studies and 106 no-tillage (NT) studies compiled for this analysis. The United States is divided into its four census regions: West, South, Midwest (MW), and Northeast (NE). CA = Canada; MX = Mexico. Obs refers to the number (n) of sample observations reported in each study.

19), biological indicators (Indicators 12, 13, 27–33, 35, 36, 39, and 40), environmental states and fluxes (Indicators 14, 23, 24–26, 34, 37, and 38), agronomic responses (Indicators 4 and 20), and general indicators (Indicators 41 and 42). Within and across classes, indicators range from representing intrinsic properties (e.g., texture) to dynamic variables (e.g., soil respiration).

The most responsive indicators (i.e., those shown in Fig. 1b and 1c), mainly fell within the biological, environmental, and agronomic groups and included four of the 19 Tier 1 indicators. Even though we classified aggregation as a physical indicator, biological activity influences aggregate formation and stability (Lynch and Bragg, 1985, Maaß et al., 2015, Vezzani et al., 2018). Infiltration, another physical indicator, showed high responsiveness even though the related indicator *K*<sub>sat</sub> (saturated hydraulic conductivity) did not, suggesting uncertainty in how cover crops enhance infiltration rates. While these findings are preliminary, they nonetheless point to a subset of indicators that may be sensitive to changing management practices and therefore that may be most useful to decision makers such as farmers, planners, and regulators.

Management decision-making can also be enhanced by considering soil health in both absolute and relative terms. Good soil health depends on a combination of location (soil type, climate) and management (cropping system, cultivation). In an analogy to human health, a doctor might measure the same vital signs on all patients yet only prescribe interventions based on individual characteristics and risks. Collecting the vital signs of different soils can help agencies and producers prioritize efforts on soils that are truly unhealthy and can also help track the relative progress of a given soil from baseline toward goal. Vital signs can also be used to assign risk factors to soils based on their individual characteristics, which can help predict resilience to impacts such as drought or extreme temperatures. Having a standardized set of protocols and indicators can therefore allow the community to better strategize and prioritize efforts to improve soil health across diverse systems.

## A Common Framework for Advancing Soil Health

We laud efforts to publicize and incentivize soil health, such as those undertaken by the NRCS and the Soil Health Institute. Still, we contend that soil health methods and metrics must be verified by land grant universities and other entities to ensure adequate peer review and testing is completed before dissemination to networks of extension agents, agencies, farmers, and other stakeholders. To accomplish this, metrics must be demonstrated across a range of management systems with consistent and reproducible outcomes, and results must be accessible. Accessibility can be facilitated by development of a common soil health framework for sharing soil health measurements and information. This effort is one that land grant universities are well positioned to lead.

A common framework for soil health data should enable compilation of findings from various studies, making it critical that measurements are gathered with consistent protocols and reporting units. For example, soil sampling should be

standardized in terms of depths and number of replicates, while accounting for different equipment and resources available to individuals and groups. The concept of depth-independent sampling was suggested to remove influences of changing bulk density and layer thicknesses when calculating soil carbon stocks (Gifford and Roderick, 2003). Applying such approaches to other soil health measurements can improve our ability to compare and contrast results from different studies. Further, to draw inferences across systems, it is critical that researchers collect a consistent set of parameters. We recommend that all studies provide soil texture (or preferably, sand–silt–clay percentages), pH, bulk density, and soil carbon, thus providing a basic set of soil vital signs. We also suggest, based on data compiled here, that studies should focus on measuring responsive parameters such as aggregate stability, infiltration rates (or preferably, *K*<sub>sat</sub> to avoid confounding influences such as initial soil water content; Stewart and Abou Najm, 2018), and microbial indicators such as enzymatic assays and biomass nitrogen and carbon. Finally, a common framework should be inclusive of all measured data—not just those results deemed significant (statistically or otherwise). By including negative results in which treatment differences are not detected alongside positive results in which they are, the soil health community will finally be able to talk about soil health in a consistent and transparent way.

## Supplemental Material

More detailed information regarding the data used to conduct the meta analyses is available in the online supplemental material, Supplemental Fig. S1–S5 and Supplemental Tables S1–S2.

## Acknowledgments

This work was supported by the US Department of Agriculture NRCS Conservation Innovation Grant #69-3A75-14-260. Funding was also provided by the Virginia Agricultural Experiment Station and the Hatch Program of the National Institute of Food and Agriculture, US Department of Agriculture (VA-160041). Funding was provided by the Virginia Tech Open Access Subvention Fund (VT OASF).

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