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A minimum suite of soil health indicators for North American agriculture

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ABSTRACT

The concept of soil health is appropriately receiving increased attention from governments, producers, corporations, and other stakeholders because of the many functions of soil that support ecosystem services and farm profitability. With this interest, there is growing need to verify and monitor changes in soil health that result from how agricultural soil is managed. There are many indicators of soil health and, although this benefits the scientific community, it complicates interpretation across studies. The North American Project to Evaluate Soil Health Measurements (NAPESHM) assessed over 30 available measurements on 124 long-term agricultural research sites with replicated soil health treatments and created new pedotransfer functions. This analysis draws on findings from NAPESHM to identify a minimum suite of effective indicators of soil health for the North American Continent. The criteria for a minimum suite of effective indicators are that they (1) primarily reflect soil health rather than inherent soil properties or fertility, (2) are responsive to agricultural management practices that exemplify soil health principles, (3) are conducive to measuring soil health at scale in terms of cost and availability, and (4) are not redundant with regard to linking different soil functions to ecosystem services. Many indicators were determined effective for use in soil health studies and based on this analysis, soil organic C concentration, aggregate stability, and 24 h C mineralization potential were selected for the minimum suite of indicators. Using this minimum suite, as few as three laboratory measurements can be made to assess and track improvement in soil functioning as a result of soil management changes. These indicators may be supplemented with new pedotransfer functions to also estimate changes in available water holding capacity. This minimal suite of soil health measurements is recommended for scaling up soil health assessments across North America, and possibly beyond.

Introduction

The concept of soil health, defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (NRCS, 2022a), has increased in popularity during the past decade because it promotes not only the well-being of farmers and ranchers, but the environment and society as well. Of the five components of soil security (capability, condition, connectivity, capital, and codification; McBratney et al., 2019), soil health is most similar to soil condition. Soil health also has strong ties to Sustainable Development Goals set forth by the United Nations, namely goals 2, 3, 6, 7, 12, 13, and 15 (zero hunger; good health and well-being; clean water and sanitation; access to affordable, reliable, sustainable, and modern energy for all; responsible consumption and production; combat climate change; and protect, restore, and promote sustainable use of terrestrial ecosystems) (Keesstra et al., 2016). While the principles set forth by the list of goals apply to all soils (e.g., urban, forests, grazing land, row crop agriculture), indicators used to assess changes in soil function have largely been developed to track improvements in row-crop agricultural soils.

Improvement in agricultural soil health has largely been centered around adoption of practices that support five principles developed by the USDA (2022) Natural Resources Conservation Services (NRCS), which are (1) maximizing soil armor, (2) minimizing soil disturbance, (3) increasing above-ground plant species diversity, (4) maximizing

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living roots, and (5) integration of livestock into cropping systems. Producers and researchers alike have developed and implemented management strategies whose aims align with the set of principles (e.g., reducing tillage, implementing cover crops, increasing rotation diversity) in part because these systems are more profitable for farmers (Bagnall et al., 2021). Soil health is consistently a major component of regenerative agricultural efforts (Newton et al., 2020), though no single definition of regenerative agriculture has been agreed on (O'Donoghue et al., 2022). Manifestation of the benefits of regenerative soil health systems requires interdisciplinary action to support the adoption of soil health practices at a global scale.

There is a growing need to assess and monitor changes in soil health that result from adoption of agricultural management systems exemplifying soil health principles because farmers desire to know how far along their soil health journey they have come; companies and foundations with environmental commitments need quantitative information to demonstrate that investment in practice change is effective; government agencies need to show results of financial and technical assistance programs that support soil health; and it is foreseeable that consumers may wish to know the health of soils producing their food, fuel, and fiber. Such assessment requires measures of soil health that can feasibly be applied at a continental scale. For example, in the U.S. alone there are approximately 2 M individual farms covering 384 M ha (USDA NASS, 2019). Soil management is performed at the field scale and most farms have multiple fields to assess, indicating a large number of samples needed to assess soil health continentally.

Early adopters of soil health management systems often tracked progress through qualitative observations (e.g., reduced ponding following a rain event, visual assessments of organic matter increases) (Poeplau et al., 2017; Romig et al., 1995), and many producers still use this approach. However, as support for soil health and related management practices have grown, so has the number of available soil health measurements (Norris et al., 2020; Stewart et al., 2018; Moebius-Clune et al., 2016). This abundance of measurements is advantageous from a research perspective because both novel measurements and relationships among measurements may contribute to new soil science knowledge. However, the sheer number of available measurements results in a lack of continuity across scientific studies and monitoring efforts, complicating interpretation of soil health evaluations.

Not only are there many soil health indicators, but they vary widely in their interpretability due to differences in sensitivity to management, linkage to soil processes and ecosystem services, and level of control exerted by inherent factors. Some measures directly indicate a change in a soil ecosystem service (those ecosystem services that soil has major contributions to; Dominati et al., 2010), while others are less direct and therefore harder to interpret. An example of a direct indicator is soil organic C, which is directly related to the service of regulating C pools, although many soil health assessments do not measure soil C to a depth needed to measure soil C stock. An example of a relatively less direct indicator is aggregate stability, which has been empirically linked to erodibility (Barthès and Roose, 2002; Bryan, 1968; Coote et al., 1988; Elwell, 1986; Miller and Baharuddin, 1986) and conceptually linked to water flow (Arshad and Coen, 1992; Hortensius and Welling, 2008; Moncada et al., 2015), yet there are mixed results in the literature on erodibility and a lack of comprehensive mathematical representation for how changes in aggregate stability affect soil hydrology (Nciizah and Wakindiki, 2015; Amézketa, 2008). This means that, even though there is consensus that greater aggregate stability is beneficial, a quantitative interpretation of the ecosystem service benefits resulting from increased aggregate stability is lacking. Therefore, it is more difficult to interpret than soil organic C stocks.

The North American Project to Evaluate Soil Health Measurements (NAPESHM) evaluated over 30 measurements of soil properties at 124 long-term agricultural research sites across North America to identify an effective minimum suite of indicators to measure soil health in row crop agricultural systems at the continental scale. We define effectiveness in this context by using four criteria by which we filtered NAPESHM measurements (Fig. 1). Specifically, we selected measurements from NAPESHM that (1) primarily reflect soil health rather than inherent soil properties or fertility, (2) were responsive to agricultural management practices that exemplify soil health principles, (3) were conducive to measuring soil health at scale in terms of cost and availability, and 4) were non-redundant with regard to linking different soil functions to ecosystem services. We drew on analysis of NAPESHM data for assessing each measurement's sensitivity to six soil health promoting management practices as indicators of the C cycle (Liptzin et al., 2022a; Rieke et al., 2022a), N cycle (Liptzin et al., 2022b), and the hydrologic cycle (Bagnall et al., 2022a; Rieke et al., 2022b) including development of new pedotransfer functions for plant available water (Bagnall et al., 2022b). We used indicator price and availability at commercial laboratories to determine which indicators were most practical to measure at scale for the North American Continent. Finally, we reduced the subset of indicators by choosing those with relatively direct links to soil functions when multiple indicators were linked to the same function.

Measurements that primarily reflect soil health

First, the full set of NAPSHEM soil measurements were categorized as (1) inherent soil properties, (2) soil fertility measurements, (3) exploratory measurements, and (4) dynamic soil properties appropriate for a soil health assessment (Table 1). Six inherent soil properties were identified, including soil texture, soil electrical conductivity, Na adsorption ratio, cation exchange capacity, and pH (Table 1, rows 1 to 6). Soil pH is a keystone soil property that influences soil fertility, contributes to the inherent characteristics of a soil, and can be impacted by management. We included pH in the list of inherent soil properties for the purposes of this study. There are situations in which pH is altered by soil management, but native soil pH is determined by soil forming factors, especially parent material and weathering (Essington, 2004; Zhang et al., 2019). Measurements of inherent soil properties are critical for contextualizing and interpreting soil health indicators because we assess soil health by sampling soil properties that result from a combination of soil management and inherent properties, which depend on soil forming factors. As an example of how this context was applied in NAPESHM analysis, soil texture and pH were included in regression models to assess the impact of inherent properties of all indicators (Bagnall et al., 2022a; Liptzin et al., 2022a, 2022b; Norris et al., 2023; Rieke et al., 2022b).

Soil fertility management interacts with soil health management to influence soil functioning and soil health expression (Grandy et al., 2022). Though fertility is related to soil health management because improved soil health affects nutrient cycling and availability, fertility management should be informed by different measurements. Properties that primarily reflected soil fertility included both primary nutrient and micronutrient elements which were extractable P, K, Ca, Mg, Na, Fe, ZN, CU, Mn, Al, B, Ba, Cd, Co, Cr, Mo, Ni, Pb, Si, Sr (Table 1, rows 7 to 10). While some soil health management practices, such as application of manures, may affect these properties it is far more likely that they will be managed through fertility programs. Therefore, these extractable elements were not considered in assessing the minimum suite of soil health indicators.

Some measurements included in NAPESHM were chosen because of their potential value to scientific discovery and perhaps one day, as soil health indicators (Table 1, Rows 11 to 15). These measurements include phospholipid fatty acid (PLFA) biomarker ratios; targeted amplicon sequencing, specifically 16S rRNA and ITS sequencing; metagenomic sequencing; and visible, near-infrared, and mid-infrared spectroscopy. In addition to providing a measure of microbial biomass, ratios of individual PLFA biomarkers may provide insight into microbial community dynamics. A variety of PLFA biomarker ratios have been proposed as soil health indicators (Norris et al., 2023). However, many ratios lack clear interpretations (Fierer et al., 2021), while others must be further

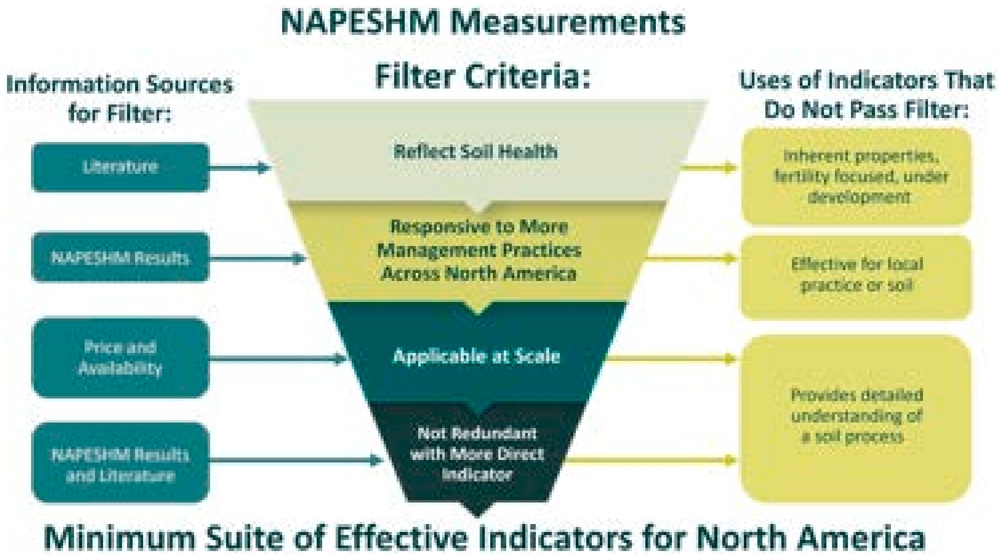

Fig. 1. Conceptual diagram of the process for filtering soil health indicators to determine a minimum suite of most effective indicators of soil health for the North American Continent. NAPESHM is North American Project to Evaluate Soil Health Measurements.

vetted prior to wide-scale use (Norris et al., 2023). Additionally, the contributions of many soil microbial community members to soil health are unknown (Fierer et al., 2021). However, information derived from microbial community structures, through targeted amplicon sequencing, can provide insight as to why traditional soil health indicators respond to management practices (Rieke et al., 2022a). Metagenomic sequencing provides information about the functional genes (e.g., C degradation and transformation, nutrient cycling) possessed by soil microbial community members. While quantification of functional genes can potentially inform soil health, specific genes must first be linked to beneficial ecosystem services (Fierer et al., 2021). Spectroscopy is a useful technology for rapid assessment of soil organic C, inorganic C, clay content, and clay mineralogy (Angelopoulou et al., 2020).

The remaining measurements of soil properties in Table 1 (rows 16 to 37) primarily reflect soil health and were analyzed in seven NAPESHM manuscripts to determine which measurements responded to management practices that exemplify soil health principles with the purpose of identifying those that were relatively more effective indicators. Four of these papers focused on the response of soil health indicators to management (Bagnall et al., 2022a; Liptzin et al., 2022a, 2022b; Rieke et al., 2022b), one considered PLFA measures (Norris et al., 2023), one compared four methods for aggregate stability (Rieke et al., 2022b), and the last developed new pedotransfer functions to predict plant available water based on soil particle size and organic C that changed as a result of management (Bagnall et al., 2022b).

Responsive to management practices which exemplify soil health principles

Following identification of soil health indicators, each was evaluated for sensitivity to soil health management practices. In this project, 2012 experimental units were sampled from 688 replicated treatments located at 124 long-term agricultural research sites across Canada, the United States, and Mexico (Norris et al., 2020). The experiments had been designed to test management effects such as tillage, cover crops, crop rotation, residue retention, and nutrient amendments (Table 2). The response of indicators to management was determined using a meta-analysis approach and compared treatments in which only one soil health management practice was different. This included fitting a meta-analytic model to predict log response ratios for soil health indicators, controlling for site as a random variable, and weighting by the number of replications of treatment pairs at each site, as detailed in Bagnall et al. (2022a), Liptzin et al. (2022a; 2022b); and Rieke et al. (2022b). Soil health indicators were determined to respond significantly to management if the 95% confidence interval predicted by the meta-analytic model did not contain zero. Response ratios were transformed to percent change for ease of interpretation (Fig. 2).

Soil organic C content (hereafter referred to as soil organic C), as measured by dry combustion, significantly increased in soils managed with reduced tillage, cover crops, organic amendments, and crop residue retention, but not with increases in rotation diversity or crop count (Liptzin et al., 2022a; Fig. 2). While soil organic C is a commonly accepted measure of C storage, other measures of soil organic C fractions have been suggested to be more readily available for microbial consumption (Moebius-Clune et al., 2016; Boyer and Groffman, 1996). Measures of this nature included in NAPESHM were permanganate oxidizable C, microbial biomass, and water extractable organic C. Additionally, organic matter measured by loss on ignition was included. The indicators were generally well correlated to soil organic C ($r = 0.56$ to $r = 0.91$) and contained similar responses to changes in management practices (Liptzin et al., 2022a; Norris et al., 2023; Fig. 2).

Most C inputs from crop residues and root exudates must be transformed by microbial community members prior to being stabilized in the soil profile. However, C mineralization *in situ* is difficult to measure and interpret due to non-standardized conditions and potential contributions from root respiration. Therefore, C cycling assays have been developed and recommended by several different soil health testing services. Three indicators of soil health related to C-cycling were assessed in NAPESHM: 24 h potential C mineralization, 96 h potential C mineralization, and β-glucosidase. All three methods were sensitive to climate and inherent soil properties (Liptzin et al., 2022a). Twenty-four-hour potential C mineralization and β-glucosidase significantly increased in systems with less tillage and increased use of cover crops, organic nutrient amendments, and residue retention; while 96 h potential C mineralization only significantly increased in systems with cover crops and organic amendments (Fig. 2). The additional sensitivity of 24 h potential C mineralization and β-glucosidase to tillage and residue retention makes the measurements more desirable indicators of soil health, when compared to 96 h potential C mineralization.

Soil N is essential for crop production, and inorganic N is commonly measured in relation to soil fertility. In the context of soil health, efficient N cycling is crucial to reducing nitrate leaching and greenhouse gas emissions. Over the past few decades, numerous measurements have been developed to understand N cycling in soil. In addition to total N,

Table 1
Soil measurements taken in the North American Project to Evaluate Soil Health Measurements (NAPESHM) categorized by whether they primarily reflect differences in inherent soil properties, soil health, or soil fertility.

	Measurement	Methodology notes	Primarily reflect	Refs.
1	Soil texture		Inherent	Gee and Bauder (1986)
2	Soil electrical conductivity		Inherent	Rhoades et al. (1989)
3	Na adsorption ratio		Inherent	Miller et al. (2013)
4	Cation exchange capacity		Inherent	Olsen and Summers (1982)
5	pH		Inherent	Thomas (1996)
6	Inorganic C (carbonates)		Inherent	Sherrod et al. (2002)
7	Extractable P		Fertility	Olsen and Summers (1982); Sikora and Moore (2014)
8	Extractable K, Ca, Mg, Na		Fertility	Knudsen et al. (1982); Sikora and Moore (2014)
9	Extractable Fe, ZN, CU, Mn		Fertility	Lindsey and Norvell (1978); Sikora and Moore (2014)
10	Extractable micronutrients	Al, B, Ba, Cd, Co, Cr, Mo, Ni, Pb, Si, Sr	Fertility	McIntosh (1969); Sikora and Moore (2014)
11	Visible near infrared diffuse reflectance spectroscopy		Exploratory	Morgan et al. (2009)
12	PLFA biomarker ratios		Exploratory	Norris et al. (2023)
13	Internal transcribed spacer (ITS) amplicon sequencing		Exploratory	Thompson et al. (2017)
14	16S rRNA amplicon sequencing		Exploratory	Thompson et al. (2017)
15	Shotgun metagenomic sequencing		Exploratory	Quince et al. (2017)
16	Total C	Dry combustion	Soil Health	Nelson and Summers (1996)
17	Organic matter	Loss on ignition	Soil Health	Moebius-Clune et al. (2016)
18	Water extractable organic C		Soil Health	Haney et al. (2018)
19	Permanganate-oxidizable carbon		Soil Health	Weil et al. (2003)
20	Microbial biomass	Phospholipid fatty acids (PLFA)	Soil Health	Buyer and Sasser (2012)
21	Potential C mineralization	24 h	Soil Health	Zibilske (2018)
22	Potential C mineralization	96 h	Soil Health	Moebius-Clune et al. (2016)
23	β-Glucosidase	pH dependent buffer	Soil Health	Tabatabai (1994)
24	Aggregate stability	Slaking image analysis	Soil Health	Fajardo et al. (2016)
25	Aggregate stability	Cornell Rainfall Simulator	Soil Health	Moebius-Clune et al. (2016)
26	Aggregate stability	Wet Sieve Procedure	Soil Health	Kemper and Rosenau (1986); Yoder (1936)
27	Aggregate stability	Mean Weight Diameter	Soil Health	Franzluebbers et al. (2000)
28	Bulk density		Soil Health	Blake and Hartge (1986)
29	Permanent wilting point	−1500 kPa	Soil Health	Reynolds and Topp (2008)
30	Field Capacity	−10 kPa, disturbed soil	Soil Health	Reynolds and Topp (2008)
31	Field Capacity	−33 kPa, intact soil cores	Soil Health	Hao et al. (2008)
32	Saturated hydraulic conductivity		Soil Health	Reynolds and Elrick (1990)
33	Total N		Soil Health	Nelson and Summers (1996)
34	Autoclaved Citrate Extractable (ACE) Protein Index		Soil Health	Wright and Upadhyay (1996)
35	Potential N Mineralization		Soil Health	Bundy and Messinger (1994)
36	N-acetyl-β-D Glucosaminidase	pH dependent buffer	Soil Health	Deng and Popva (2011)
37	Water extractable organic N		Soil Health	Haney et al. (2018)

Table 2
Definition of management practices in the North American Project to Evaluate Soil Health Measurements.

Crop Count	Comparison of monoculture treatments to treatments containing more than one cash crop.
Rotation Diversity	Binary comparison of treatments containing only grain crops to rotations with additional types of crops. The additional types were predominately legumes, but also included canola (*Brassica napus*), safflower (*Carthamus tinctorius*), and cotton (*Gossypium hirsutum*).
Residue Retention	Binary comparison of treatments that contained identical management other than the amount of biomass removed following grain harvest.
Organic Amendments	Binary comparison of treatment receiving organic amendments to those receiving only inorganic nutrient amendments. Organic amendments included biosolids, compost, herbaceous materials, and manure.
Cover Crops	Comparison of treatments which included a cover crop in at least one year of the cropping system to those not containing cover crops.
Reduced Tillage	Treatments were classified using the standard tillage intensity rating (STIR, NRCS) value for the most disruptive implement for each treatment. Paired disturbance treatments were selected if the management was the same, except for tillage implements and standard tillage intensity ratings.

indicators related to N cycling measured in NAPESHM were potential N mineralization, autoclaved citrate extractable protein, N-acetyl-β-D-glucosaminidase, and water extractable organic N. Total N and autoclaved citrate extractable protein significantly increased in systems with decreased tillage, cover crops, organic amendments, and residue retention (Liptzin et al., 2022b; Fig 2). Water extractable organic N significantly increased in systems with decreased tillage, organic amendments, and residue retention, while potential N mineralization and N-acetyl-β-D-glucosaminidase significantly increased in systems with cover crops, organic amendments, and residue retention (Fig. 2). The additional sensitivity of total N and autoclaved citrate extractable protein makes these two indicators more desirable compared to water extractable organic N and potential N mineralization.

The indicators of soil health related to water storage and transport measured in NAPESHM were saturated hydraulic conductivity, bulk density, volumetric water retention at permanent wilting point (approximated at −1500 kPa), volumetric water retention at field capacity measured both on intact (−33 kPa) and repacked cores (−10 kPa), and aggregate stability. Four methodologies for measuring aggregate stability were used in the NAPESHM project; water stable

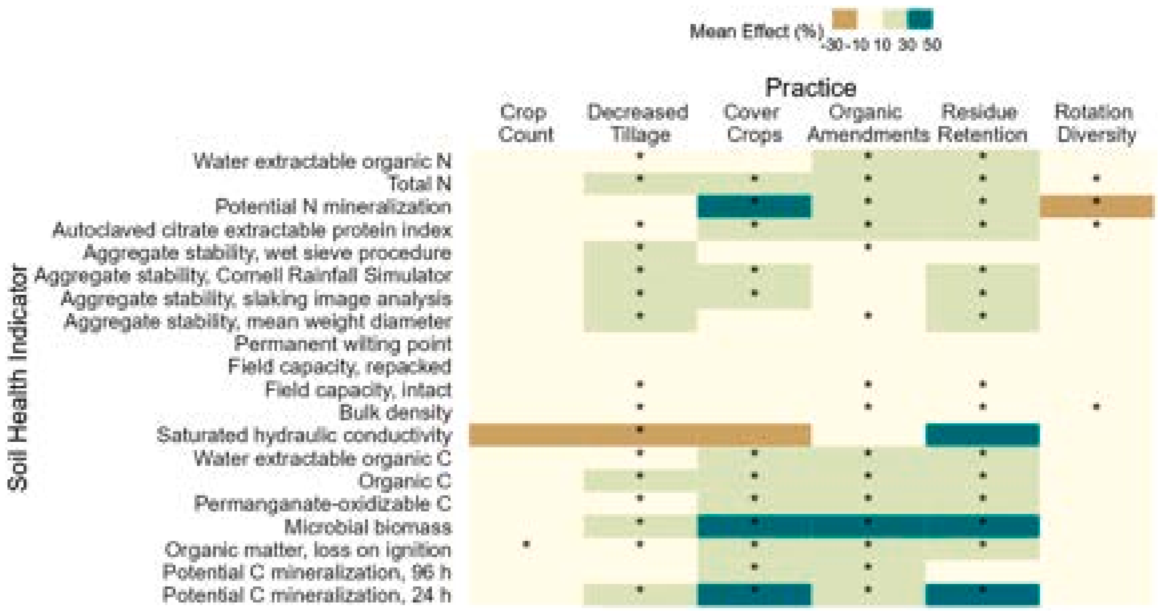

Fig. 2. Heat map of the mean effect (% change) of soil health management on indicators of soil health in the North American Project to Evaluate Soil Health Measurements. Asterisks designate significant (95% confidence interval) effects of the practice on the mean response of the soil health indicator.

aggregates using the Cornell Rainfall Simulator (Moebius-Clune et al., 2016), wet sieved water stable aggregates (Kemper and Rosenau, 1986), slaking captured and adapted from SLAKES smart-phone image recognition software (Fajardo et al., 2016), and the mean weight diameter of water stable aggregates (Franzluebbers et al., 2000). Rieke et al. (2022b) compared all four measures of aggregate stability, and the remainder of water-related indicators were assessed by Bagnall et al. (2022a).

All four methods of aggregate stability were similarly responsive to management practices in the NAPESHM project, though not all with the same significance or magnitude to each management practice (Rieke et al., 2022b). No single method was clearly superior for measuring the effects of all management practices, although wet sieved water stable aggregates contained less significant responses to management when compared to the other methods (Rieke et al., 2022; Fig. 2), and is therefore not recommended. Regardless of method chosen to measure wet aggregate stability, consistency of method is recommended within any given study. As well, specific studies may benefit from using a particular method to detect changes caused by a particular practice. For example, water stable aggregates using the Cornell Rainfall Simulator (Table 1, row 25) responded to residue retention, while wet sieved water stable aggregates (Table 1, row 26) did not, so studies of residue retention may be more likely to detect changes using the Cornell Rainfall Simulator than when using wet sieved water stable aggregates, while the reverse was true for organic nutrient amendments.

Water and soil structure related indicators had a broad range in outcomes. Due to time constraints, saturated hydraulic conductivity was measured only once per experimental unit (i.e., plot), and results were inconclusive because lack of replication within a plot led to a relatively large variance and inability to capture the true mean (Bagnall et al., 2022a). Nonetheless, saturated hydraulic conductivity can be a useful measurement of soil health and functioning, but the requirement of taking more observations hinders applicability on farms and achieving scale. Water retention measured on disturbed soil samples, both at field capacity and permanent wilting point, did not respond significantly to any management practice (Bagnall et al., 2022a; Fig. 2). Water retention at field capacity measured on *intact* soil cores was responsive to reduced tillage, organic amendments, and residue retention (Fig. 2). Of the water-related indicators; field capacity measured on intact cores; bulk density; and water stable aggregates using the Cornell Rainfall Simulator, mean weight diameter of water stable aggregates, and slaking image analysis were all suitable indicators in terms of their response to management. In addition, Bagnall et al. (2022b) fit new pedotransfer functions for plant available water using NAPSHM data (including intact cores) that showed greater response of available water to increases in soil C than past research has shown (Minasny and McBratney, 2018). These new pedotransfer functions enable soil health interpretations related to soil water availability (e.g., drought resilience) in cases where soil C is measured as a soil health indicator and soil clay and sand content are known.

Across the NAPESHM papers, the majority of soil health indicators measured were sensitive to tillage, residue management, cover cropping, and organic additions, although few were sensitive to increased rotation diversity and one to crop count (Fig. 2). These encouraging results confirm the utility of a broad array of indicators that scientists use to evaluate management impacts on soil health.

Applicable for measuring soil health at scale

Following evaluation of responsiveness to soil health management practices, indicators most responsive to the variety of practices were assessed in terms of continental scalability. Growing stakeholder interest has led to large-scale soil health and C measurement campaigns (Bruner and Brokish, 2021), requiring analysis of many thousands of soil samples. Specific efforts to measure and monitor soil health at scale include USDA-NRCS financial assistance for soil health analysis (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/), USDA-NRCS research in dynamic soil properties (Wills et al., 2017), efforts by the Soil Health Partnership (Wood and Bowman, 2021), and funding opportunities for assessing management impacts on soil carbon and greenhouse gas emissions (USDA, 2022).

Originally, most soil health indicators were developed for scientific research purposes, with many requiring specialized equipment or expertise. To be applied on working lands at a continental scale, soil health indicators must also be available at commercial labs for a reasonable price. Growing interest in measuring soil health has expanded testing services from a handful of testing laboratories located on university campuses to multiple privately-owned soil testing services. These private laboratories must consider required skillsets of operators, capital equipment and consumable costs, spatial and temporal assay footprints, and labor costs prior to adding an indicator to testing services they provide. To minimize cost, such laboratories aim to employ measurement methods that limit labor. Consequently, we considered whether soil health indicators were appropriate for use at scale by accounting for their availability and cost in commercial labs.

Indicators that were sensitive to management but not widely available, include field capacity measured on intact cores, aggregate stability measured using the Cornell simulated rainfall apparatus, and aggregate stability measured by mean weight diameter. Field capacity measured on intact cores is not offered at any commercial laboratory and was conducted at the Cornell Soil Health Testing Laboratory by special agreement for NAPESHM. Aggregate stability measured by the Cornell simulated rainfall apparatus is not currently available at commercial laboratories due to the time-consuming nature of the method. To our knowledge, it is offered at two publicly owned laboratories, the Cornell Soil Health Testing Laboratory and at Oregon State University Soils Laboratory. Similarly, to our knowledge, the mean weight diameter of water stable aggregates is not currently available at any commercial laboratory.

Other measures are more readily available but have other limitations at scale. While availability of commercial labs to measure bulk density is currently expanding because of voluntary carbon markets, collection of bulk density is not only labor intensive, but difficult to collect correctly, and is costly to analyze as well (approximately $20 per sample, personal communication). Although it is available at multiple commercial laboratories, microbial biomass, measured as the sum of specific PLFA biomarkers, is also costly to analyze ($50–60 per sample, personal communications). Saturated hydraulic conductivity was not found to be responsive to management in this study. The cost of labor and skill needed to collect samples and quality control data reliably would likely prevent broad use as a soil health indicator even though research experiments and meta-analyses have detected responses to management (e.g. Basche and DeLonge, 2017).

Indicator links to soil functions and ecosystem services

Ecosystem services flow from soil functions that depend on a combination of inherent soil properties and soil health (Dominati et al., 2010). In many cases, increased soil health can increase the provision of ecosystem services by improving soil functions. Both soil health and ecosystem services are boundary concepts – concepts that promote communication by enabling people across disciplines and stakeholder groups to use common language (Schleyer et al., 2017). Soil health provides a framing for soil scientists to interact with farmers (Romig et al., 1996) and soil ecosystem services relate soil management outcomes to society (Dominati et al., 2010). A goal of measuring soil health indicators is to provide land managers with information on how well their soil is functioning, along with the ecosystem services that are being delivered. Therefore, we considered which NAPESHM soil health indicators were linked to soil ecosystem services via relationships with soil functions.

Soil health can contribute to ecosystem services that flow from soils functioning as a living ecosystem. The ecosystem services that soil health indicators are most commonly used to inform are biomass production; storing, filtering, and transforming nutrients and water; hosting biodiversity; and regulating C pools (Aadhikari and Hartemink, 2016). With our current knowledge, improving soil health would have limited or no contribution to the ecosystem services of sourcing raw materials, storing geological or architectural artifacts, or providing a platform for human activities. Certain cultures do link changes in soil health to heritage values (Stronge et al., 2020), while universal indicators are not widely recognized.

Although soil ecosystem services were not measured in NAPESHM, indicators of soil health can be linked to ecosystem services through their conceptual relationships to soil functions. We found eight indicators of soil health that were suitably responsive to management and feasible to measure at scale. To further reduce these eight soil health indicators to a minimum suite of indicators conducive to scaling, we grouped each indicator to one ecosystem service to which they are most proximal and selected the most effective indicator from each group. We recognize that soil C, N, and water associated indicators are all mechanistically related to biomass production and C cycling.

Six indicators that were responsive to management and applicable at scale were most proximally related to C pools and cycling: permanganate-oxidizable C, organic C, organic matter, potential C mineralization after 24 h, β-glucosidase, and water extractable organic C (Liptzin et al., 2022a) and all six were strongly correlated and showed similar responses to management (Fig. 2). While these C-related indicators are all related conceptually to the ecosystem service of regulating C pools, it is notable that potential C mineralization after 24 h was also related to differences in bacterial and archaeal community structure (Rieke et al., 2022a) and has been linked to changes in microbial biomass (Fierer and Schimel, 2003). Although all of these C indicators are useful for soil science research, we recommend that organic C and potential C mineralization after 24 h be used for soil health assessment at scale and used to indicate the ecosystem services of regulating C pools, transforming nutrients, and hosting biodiversity.

Two indicators that were responsive to management, suitable to measure at scale, and related to N pools or cycling were total N and autoclaved citrate extractable protein. In soil health contexts N is strongly associated with the ecosystem service of nutrient cycling. Total N and autoclaved citrate extractable protein were highly correlated (Liptzin et al., 2022b), but total N had somewhat greater response to management, especially decreased tillage (Fig. 2). Total N is strongly correlated with organic C and so a minimum suite of soil health indicators that includes organic C does not also need to include total N. Because of the strong correlation between organic C and total N (r^2=0.92), organic C can be used in soil health assessments to inform stakeholders about the ecosystem service of nutrient cycling.

Lastly, we recommend that the indicator included in the minimum suite for assessing soil structure and soil hydraulic properties at scale is aggregate stability using slaking image analysis. Aggregate stability is related to the ecosystem services of storing, filtering, and transforming nutrients and water, and regulating carbon pools. Furthermore, when soil texture data are available, stakeholders may add predictions of the change in plant available water to these indicators to supplement interpretations about water storage, carbon cycling, and biomass production (e.g., drought resilience) (Bagnall et al., 2022b).

Although there is general understanding that increased soil health means a soil is functioning better and can therefore provide greater ecosystem services, such services do operate within the limits of inherent soil properties and climate (Ellili-Bargaoui et al., 2021; Devine et al., 2021; Bunemann, 2018). This means that interpretation of soil health indicators requires local context, and that in addition to measuring this minimum suite of indicators, soil health interpretations must also recognize and identify the soil type measured and the clime in which it resides so that comparisons of soil health indicators are only made between sufficiently similar soils. In addition to recognizing where the soil is located, soil texture (i.e., particle size) may also need to be measured if not already known. Further, measurement of organic C may require subtraction of inorganic C from total C if measured in calcareous or recently limed soils (Nelson and Sommers, 1996).

Final indicator set

A summary of the outcomes of filtering all the measurements and associated indicators through the logic model in Fig. 2 is presented in Table 3, along with the methodology recommended for each indicator that balances cost and availability. The selected suite of indicators is currently available for approximately fifty U.S. dollars (total C and N $15-25, aggregate stability $5-10, and 24 h C mineralization potential $15-28, personal communications). In application, it is expected that practical circumstances may determine other methodologies. For

Table 3
Summary of the outcomes of filtering all the measurements and associated indicators in Table 1 through the logic model in Fig. 1.

Indicator	Measurement	Measurement Refs.
Organic C	Dry combustion, where organic C is measured as total C, except for calcareous soils. In calcareous soils, organic C is measured as total C minus inorganic C.	Nelson and Sommers (1996)
Potentially mineralizable C	24 h CO_2 burst resulting from rewetting air dried, sieved soil.	Zibilske (2018)
Aggregate stability	10-min change in slaking via image analysis.	Fajardo et al. (2016)
Available water holding capacity	Predicted using organic carbon and texture.	Bagnall et al. (2022b)

example, limited access to quality laboratories may necessitate the use of spectroscopy for organic C, and plant available water. When monitoring changes in soil health over time, it is most important to maintain consistency in the method selected.

Limitations

The goal of this project was to identify and recommend a minimum suite of effective indicators of soil health at scale for the North American Continent. Different goals may lead to selection of other indicators or measurement methodologies. For example, assessing soil organic C stocks would require inclusion of bulk density and coarse fragments, as well as sampling deeper than 15 cm. Although they are comprehensive, findings from the North American Project to Evaluate Soil Health Measurements are limited to the North American Continent, or areas with similar climates and soils. Similar sampling and evaluation programs in other locations around the world would better inform land managers, soil scientists, and stakeholders on the universal applicability of this minimum suite of soil health indicators found applicable for North America. In addition, some assessments of indicators were limited by our experimental design (i.e., saturated hydraulic conductivity) and others are being refined actively by the soil science and soil health community (e.g., targeted amplicon sequencing and metagenomics), so future studies and other experimental designs may offer additional findings.

The NAPESHM field sites represent long-term adoption of soil health management practices, but they do not probe the limits of how heathy soils can become through management. Because management practices are applied differently, they may induce greater or lesser changes in soil health indicators than observed in this study. The objective of the study was to evaluate management practices at the component level and not at the systems level. Management interactions may result in outcomes not captured by this dataset. However, such synergies in a soil health management system are expected to be important for improving soil health. Further, there is great value in measuring soil health on the farm, in addition to replicated research plot experiments.

Future directions

Researchers and private laboratories continue to develop new indicators and modify existing protocols. The development of new indicators tends to focus on capturing biological processes not adequately assessed by current soil health indicators (Fierer et al., 2021), while methods for capturing physical and chemical parameters of known importance are refined to enhance efficiency and scalability (Morgan et al., 2009; Fajardo et al., 2016). Recent advances in DNA sequencing techniques have led to an abundance of data aimed at characterizing efficient carbon and nutrient cycling, impacts of soil pollutants (e.g. heavy metals, pesticide applications), and crop pathogen presence. However, rapidly changing technologies and non-standard data processing pipelines promote a lack of continuity across results. Additionally, the current cost and specialized expertise needed to analyze high throughput sequence data may limit the continental scaling of these measurements. Still, these data may be used to identify important genetic targets that can be quantified and scaled using simpler techniques, such as quantitative polymerase chain reactions. While not currently available, integration of microbiome data with existing soil health indicators provides an opportunity to expand stakeholder knowledge of vital soil functions.

Over the past few decades, numerous soil health indicator protocols that were originally developed by research communities have been modified to permit scaling by private laboratories. One example of indicator method refinement is aggregate stability. The original method developed by USDA-ARS necessitates specialized equipment and a labor-intensive process (Yoder et al., 1936), which effectively drives increased costs by private laboratories. Understanding the importance of the indicator, researchers at the University of Sydney developed a smart-phone application to capture changes in aggregate stability that are well correlated with the traditional method (Fajardo et al., 2016; Rieke et al., 2022b). Similar soil organic carbon method refinement is evolving using visible, near-infrared and mid-infrared spectroscopy data. Currently, near-infrared spectroscopy currently requires a greater number of measurements using an in-field probe to capture soil variability comparable to traditional soil health indicators, while mid-infrared spectroscopy library data must be built to allow measurement across soil types. As the technologies are reliable and provide the accuracy needed for measurement and interpretation, we support their use.

Conclusion

The results from NAPESHM support that there are many suitable indicators of soil health used in research, however method consistency for individual studies is recommended. In the context of measuring and monitoring soil health at scale for the North American Continent the following minimum suite of indicators are recommended: 1) soil organic C, 2) aggregate stability via slaking image recognition, and 3) C mineralization potential. This work also developed new pedotransfer functions to predict changes in plant available water holding capacity in response to changes in soil organic C. Together, these three indicators and predicted available water holding capacity can inform stakeholders on how soil health management practices affect soil's ability to support biomass production; store, filter, and transform nutrients and water; host biodiversity; and regulate C pools. This minimal suite of soil health indicators is expected to increase the number of stakeholders capable of quantitatively testing and monitoring their soil, which in turn, may increase adoption of management practices that result in healthier soils.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are not currently publicly available.

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