Received: 16 March 2020 | Accepted: 18 March 2020 | Published online: 6 May 2020

DOI: 10.1002/agj2.20234

Agronomy Journal

FORUM

Introducing the North American project to evaluate soil health measurements

Charlotte E. Norris | **G. Mac Bean** | **Shannon B. Cappellazzi** | **Michael Cope** | **Kelsey L.H. Greub** | **Daniel Liptzin** | **Elizabeth L. Rieke** | **Paul W. Tracy** | **Cristine L.S. Morgan** | **C. Wayne Honeycutt**

Soil Health Institute, 2803 Slater Road, Suite 115, Morrisville, NC 27560, USA

Correspondence
Soil Health Institute, 2803 Slater Road, Suite 115, Morrisville, NC 27560, USA.
Email: cmorgan@soilhealthinstitute.org

Funding information
Foundation for Food and Agriculture Research; Samuel Roberts Noble Foundation; General Mills

Abstract

The North American Project to Evaluate Soil Health Measurements was initiated with the objective to identify widely applicable soil health measurements for evaluation of agricultural management practices intended to improve soil health. More than 20 indicators were chosen for assessment across 120 long-term agricultural research sites spanning from north-central Canada to southern Mexico. The indicators being evaluated include common standard measures of soil, but also newer techniques of visible and near-infrared reflectance spectroscopy, a smart phone app, and metagenomics. The aim of using consistent sampling and analytical protocols across selected sites was to provide a database of soil health indicator results that can be used to better understand how land use and management has affected the condition of soil ecosystem provisioning for agricultural biomass production and water resources, as well as nutrient and C cycling. The objective of this paper is to provide documentation of the overall design, and methods being employed to identify soil health indicators sensitive across agricultural management practices, pedologies, and geographies.

1 | INTRODUCTION

There is a growing understanding by farmers, agricultural industry, food and beverage companies, and policymakers that soil management practices need to include goals and measures of long-term environmental sustainability to address contemporary pressures (e.g., climate change, water quality) and to satisfy changing consumer awareness. This awareness is driven by the knowledge that our population is projected to reach more than 9.7 billion people by 2050 (United Nations, 2017), substantially increasing pressure on our soil and other natural resources. Soils play an essential role in provisioning ecosystem services including food, fiber, and fuel, being an integral part of water and nutrient cycles, supporting biodiversity, mitigating and adapting to climate change, and human spiritual and cultural needs. The global pressures on agricultural lands are often anthropogenic in origin, for example, climate change, erosion, or land-use change (FAO, 2015; Smith et al., 2016). Therefore, our contemporary issue is how to best manage our agricultural land under these societal challenges to strengthen long-term environmental sustainability and resilience (IPCC, 2019). The most straight-forward road to achieving sustainability is to care for our soil resource through the promotion and maintenance of soil health.

Abbreviations: 16S rRNA, 16S ribosomal ribonucleic acid; AWHC, available water holding capacity; CEC, cation exchange capacity; DTPA, diethylenetriaminepentaacetic acid; EC, electrical conductivity; EU, experimental unit; ITS, internal transcribed spacer; K_{fs}, saturated hydraulic conductivity measured in the field; NAPESHM, North American Project to Evaluate Soil Health Measurements; PLFA, phospholipid fatty acid; SAR, sodium adsorption ratio; VisNIR, visible and near-infrared reflectance spectroscopy.

Core Ideas

- Identification of measurements for analysis of soil condition.
- Identification of long-term soil health agricultural management research trials.
- Continental-scale soil sampling to account for intrinsic soil properties and climate.
- Approach for linking soil properties and management history to ecosystem services.

But what is soil health? The concept of soil health has been given various names over the last century, but our understanding of the concept has evolved as well. Contemporary definitions developed by soil scientists have stated that soil health is "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health" (Doran, Sarrantonio, & Liebig, 1996). Kibblewhite, Ritz, and Swift (2008) provided a definition with a stronger agricultural context that included capability to produce food and fiber along with providing other ecosystem services. For the International Year of Soils, the Food and Agriculture Organization of the United Nations officially adopted the World Soil Charter (FAO, 2015). Principle 5 of the Charter states "soil health management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity". Within society, we recognize all definitions. For clarity succinctness, here we use the definition, used by the U.S. Department of Agriculture Natural Resource Conservation Service (USDA-NRCS), where soil health "is the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans."

Promotion and maintenance of soil health presents a multifaceted challenge. The first part of the challenge is determining what we value, or ask, from a specific soil because soils provide many ecosystem services, but not all soils can provide all services equally nor simultaneously. Ecosystem services is one framework that classifies the benefits of soils including: a foundation for infrastructure, a cultural heritage, and habitat for organisms, in addition to the commonly recognized provision of food, fiber, and fuel (FAO, 2015). In agricultural soils, there have often been trade-offs between food production and other ecosystem services. For example, tillage of soil for crop production has been identified with decreased organic matter (Post & Mann, 1990), high fertilizer use on croplands is associated with higher nutrient concentrations in agricultural watersheds (Caraco & Cole, 1999), and grazing can increase erosion in arid rangelands (Jones, 2000). When we address soil health, we specifically refer to agricultural soil health as it relates to the ecosystem services of food production, water supply and regulation, nutrient cycling, and carbon cycling. We assess soil health through the lens of on-farm soil functioning for food production (e.g., providing water, nutrients, and physical support for growth) in addition to its off-farm soil functions (e.g., retention and purification of water, flood regulation, habitat provisioning, and C storage).

A second part of the soil health challenge must also be addressed. This is understanding and communicating what the capacity, or inherent ability, of a soil to support the desired service is–in other words, defining what is "healthy" for a specific soil and its service. This part is reflected in the Doran et al. (1996) definition of soil health which added the qualifier of "within ecosystem and land-use boundaries". Because soils develop based on the five soil-forming factors (climate, organisms, relief, parent material, and time), their abiotic and biotic properties will vary across the landscape. A soil's individual functions (e.g., nutrient or water cycling) are relative to inherent properties (e.g., parent material or texture) and location; for that reason, a soil's health is best evaluated against a reference state (e.g., soil genoforms vs. phenoforms [Rossiter & Bouma, 2018]). For example, a soil developing on a sandstone parent material will always differ from a soil developing on shale in terms of water and nutrient relations. Understanding soil health is therefore contextual, and healthy soils do not represent identical capacities to function across a landscape. A healthy agricultural soil on the north-central plains of North America (e.g., Dark Brown Chernozem in Lethbridge, AB, Canada, also known as a Mollisol) is, therefore, inherently different to a healthy soil in subtropical southeastern North America (e.g., Plinthic Kandiudults in Quincy, FL), or a tropical soil in southern North America (e.g., Cambisol in Santa Domingo Yanhuitlán, OA, Mexico, also known as an Inceptisol). This diversity in inherent soil properties leads to ambiguity when communicating about soil health–especially in terms of management practices. Lack of clarity in terminology confounds our understanding and challenges researchers to determine reliable and robust measures for farmers and policymakers that promote soil health for agricultural and environmental sustainability across the landscape.

This is not a new challenge. Humans have recognized the inherent variability of soil and managed the resource accordingly for centuries (e.g., as reviewed in Doran et al., 1996). There was a period of intense interest and demand by land managers for improved measures of soil health at the end of the 20th century (Doran, 2002). Researchers responded by, not only looking at individual indicators, but also developing integrated tools to measure soil health (Karlen, Goeser, Veum, & Yost, 2017). These tools integrated several soil property measurements that were both easy to assess and were perceived to be sensitive to changing management practices. Three tools that currently assess soil health include the Soil Health Management Assessment Framework (Andrews, Karlen, & Cambardella, 2004), Haney Soil Test (Haney, Haney, Hossner, & Arnold, 2010), and Cornell's Comprehensive Assessment of Soil Health (Moebius-Clune, Moebius-Clune, Gugino, Idowu, & Schindelbeck, 2017), and each relies on a specific suite of measures of soil physical, chemical, and biological properties. These three soil health tools are valuable for their ease in collection, analysis, interpretation, and, therefore, in cultivating an awareness of sustainable agricultural management practices. However, when the tools have been applied to research sites, they do not consistently capture improvements in soil health (Chahal & Eerd, 2018; Roper, Osmond, Heitman, Wagger, & Reberg-Horton, 2017; van Es & Karlen, 2019). Questions remain regarding application, ease-of-use, and scope for these metrics.

With global challenges increasing our need for resilient and long-term sustainable soil, there has been a resurgence of interest in soil health and recent critical assessments of our understanding of it (e.g., Bünemann, Bongiorno, Bai, Creamer, & Deyn, 2018; Rinot, Levy, Steinberger, Svoray, & Eshel, 2018). What is missing, and is therefore timely and necessary, is a large-scale broad assessment of soil health indicators, both old and new, across a wide range of soils, climates, and management systems. This project, the North American Project to Evaluate Soil Health Measurements (NAPESHM), aims to provide this assessment. This is a continental-scale project using long-term (>10 yr) agricultural experiment research sites to develop relationships between changes in soil condition as a function of soil properties, climate, and management practices–that is, to identify the sensitivity of widely applicable soil measures to changes in soil condition from soil health management practices. To achieve the project's overall objective, four initial objectives of selecting the relevant measures, sampling sites, collection of samples, and acquisition of analytical data must be met. Here we outline the approach taken to meet the initial objectives through (a) identifying measurements of interest in soil health; (b) establishing partnerships with long-term agricultural experiment field sites in Canada, Mexico, and the United States; and (c) developing a soil sample collection protocol for all measures. This project could only be realized through the vision and cooperation of Partnering Scientists from across North America who have volunteered their long-term research sites to be a part of the project, and the financial support provided by numerous funders.

2 | PROJECT DESCRIPTION

2.1 | Inception

In 2013, the Farm Foundation (established in 1933) and the Samuel Roberts Noble Foundation (established in 1945) initiated the Soil Renaissance effort. The Soil Renaissance organized several workshops which brought together a committee of scientists from public and private sectors, farmers, field conservationists, and soil test laboratories to review appropriate indicators and measurement techniques for soil health. The professional judgement of these groups assessed different measures of soil properties and the corresponding analytical methods considered as sensitive to changes in soil health. Based upon that effort, 28 soil measures were selected for this project as indicators of soil health (Table 1). Their assessment criteria were for the measurement (a) to be applied regionally and, when taking soil inherent properties into account, applied across the continent; (b) have a clear range of responses based on desired agricultural goals; and (c) be responsive to varying management practices. However, this was the ideal and, in the final selection, not all measures chosen met these criteria. Some additional measures of soil properties were also included because they hold promise but required further research. In addition, three existing soil health evaluation programs, namely, Soil Health Management Assessment Framework (Andrews et al., 2004), the Cornell Comprehensive Assessment of Soil Health (Moebius-Clune et al., 2017), and the Haney Soil Test (Haney et al., 2010) were selected for evaluation (using the analytical methodologies specified within each program; Table 2).

2.2 | Indicators

2.2.1 | Measures of soil physical properties

The soil physical properties measured for this project include soil particle size analysis, aggregate stability, soil water content at field capacity and permanent wilting point, bulk density, and saturated hydraulic conductivity measured in the field ($\boldsymbol{K}_{\mathrm{fs}}$) (Table 1). In this context soil particle size distribution is an inherent soil property, not a soil health indicator. However, particle size is necessary for referencing many soil health measures. Agricultural production systems rely on inherent soil physical properties (Letey, 1985), especially as they relate to the capture and storage of water, the creation of habitat for microorganisms and roots, basic plant nutrient supply from clay weathering, and transport of solutes and fine particles. However, conflicting results exist when relating soil management practices to these properties (Blevins, Thomas, Smith, Frye, & Cornelius, 1983; Chaudhary, Singh, Pratap, Pratap, & Sharma, 2005; Hill, 1990; Ismail, Blevins, & Frye, 1994; Tormena, Logsdon, & Cherubin, 2016). Therefore, including these measurements as part of this geographically diverse project is expected to refine knowledge of the relationships among management practices and inherent and manageable soil physical properties. While most soil physical property indicators were measured using standard methods

TABLE 1 Selected indicators of soil properties chosen for the North American Project to Evaluate Soil Health Measurements (NAPESHM) along with each analytical method

Properties	Indicators	Method	Reference
Soil physical	Soil texture	Pipette method with three size classes (2000-50, 50-2, and <2 µm)	Gee & Bauder, 1986
	Bulk density	Core method of 7.6 cm diam. and 7.6-cm depth	Blake & Hartge, 1986
	Aggregate stability	Wet sieve procedure with weight measurement	Kemper & Roseneau, 1986
	Water content	Ceramic plate method measured at –33 kPa on intact cores and –1500 kPa on repacked soils	Klute, 1986
	Soil stability index	Combination of wet and dry sieving at multiple sieve sizes	Franzluebbers et al., 2000
	Water infiltration rate K_{fs}	Two-ponding head method	Reynolds & Elrick, 1990
Soil chemical	Soil pH	1:2 soil/water	Thomas, 1996
	Soil electrical conductivity	1:2 soil/water	Rhoades, 1996
	Extractable P	Mehlich-3 extractant for all and Olsen extractant when soil pH ≥ 7.2	Olsen & Sommers, 1982 or Sikora & Moore, 2014
	Extractable K, Ca, Mg, Na	Mehlich-3 extractant for all and ammonium acetate extraction when soil pH ≥ 7.2	Knudsen et al., 1982 or Sikora & Moore, 2014
	Extractable Fe, Zn, Cu, Mn	Mehlich-3 extractant for all and DTPA when soil pH ≥ 7.2	Lindsay & Norvell, 1978 or Sikora & Moore, 2014
	Cation exchange capacity	Sum of cations from Mehlich-3 extrant for all and ammonium acetate when soil pH ≥ 7.2	Olsen & Sommers, 1982 or Sikora & Moore, 2014
	Base saturation	Calculation of cations from Mehlich-3 extractant for all and ammonium acetate when soil pH ≥ 7.2	Olsen & Sommers, 1982 or Sikora & Moore, 2014
	Sodium adsorption ratio	Saturated paste extract followed by inductively coupled plasma spectroscopy	Miller et al., 2013
Soil biological	Soil organic C	Dry combustion, corrected for inorganic C, if present, using pressure-calcimeter	Nelson & Sommers, 1996 or Sherrod et al., 2002
	Active C	Permanganate oxidizable carbon (POXC) digestion followed by colorimetric measurement	Weil et al., 2003
	Short-term C mineralization	4-d incubation followed by CO_2–C evolution and capture at 50% water-filled pore space	Zibilske, 1994
	Total N	Dry combustion	Nelson & Sommers, 1996
	Nitrogen mineralization rate	Short-term anaerobic incubation with ammonium and nitrate measured colorimetrically	Bundy and Meisinger, 1994
	Soil protein index	Autoclaved citrate extractable	Schindelbeck, 2016
	β-glucosidase	Assay incubation followed by colorimetric measurement	Tabatabai et al., 1994
	β-glucosaminidase	Assay incubation followed by colorimetric measurement	Deng & Popova, 2011
	Phosphatase	For soil pH ≥ 7.2, alkaline phosphatase, otherwise acid phosphatase. Assay incubation followed by colorimetric measurement	Acosta-Martinez & Tabatabai, 2011
	Arylsulfatase	Assay incubation followed by colorimetric measurement	Klose et al., 2011
	Phospholipid fatty acid	Bligh–Dyer extractant, solid phase extraction, transesterification, and gas chromatography	Buyer & Sasser, 2012
	Genomics	16S rRNA, ITS, and shotgun metagenomics	Thompson et al., 2017 and Quince et al., 2017
Other	Reflectance	vis/NIR diffuse reflectance spectroscopy	Veum et al., 2015
	Crop yield	Obtained from historical plot yield	

TABLE 2 Soil health tools included as part of the North American Project to Evaluate Soil Health Measurements, and the measures they incorporate

Framework	Abbreviation	Measures included in framework	Included in this project
Soil Management Assessment Framework	SMAF[a]	Nematode maturity index	
		Metabolic quotient determined from soil respiration and microbial biomass	
		Bulk density	✓
		Total organic C	✓
		Microbial biomass C	
		Potentially mineralizable N	✓
		Soil pH	✓
		Soil test P	✓
		Macroaggregate stability	✓
		Soil depth	
		Available water holding capacity	✓
		Electrical conductivity	✓
		Sodium adsorption ratio	✓
Comprehensive Assessment of Soil Health	CASH[b]	Soil texture - modified method utilizing sieves and decanting	✓
		Available water capacity by pressure plate	✓
		Surface hardness by penetrometer	
		Subsurface hardness by penetrometer	
		Aggregate stability by rainfall simulator	✓
		Organic matter by loss on ignition	✓
		Soil protein by autoclaved citrate extractable protein index	✓
		Soil respiration by CO_2–C analysis following 4-d incubation of moist soil	✓
		Active C by colourimetric changes to K permanganate solution	✓
		Soil pH by 1:2 soil water suspension	✓
		Basic extractable P, K, Mg, Fe, Zn and enhanced extractable Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Mn, Na, Ni, Pb, S, Sr by modified Morgan's solution (ammonium acetate and acetic acid)	✓
Soil Health Tool	HANEY[c]	CO_2–C analysis following 24-h incubation of moist soil	✓
		Water extractable organic C and N	✓
		Oxalic, malic, and citric acid (H3A) extractable P, K, Mg, Ca, Na, Zn, Fe, Mn, Cu, S, and Al	✓
		Total water and H3A extractable NO_3–N, NH_4–N, and PO_4–P	✓

[a] Andrews et al. (2004).
[b] Moebius-Clune et al. (2017).
[c] Haney et al. (2018).

(e.g., the pipette method as explained in Gee & Bauder, 1986; Table 1), several newer approaches are also evaluated. For example, aggregate stability is measured using the standard "wet aggregate stability test" (Kemper & Roseneau, 1986), the Cornell wet aggregate stability test (Moebius-Clune et al., 2017), and a soil aggregate stability smartphone application (i.e., SLAKES; Fajardo, McBratney, Field, & Minasny, 2016). Because the SLAKES method requires only a smartphone, the method is significantly cheaper and more accessible and therefore a more viable measurement if it performs similarly to the other methods. Likewise, the two-ponding head method used to measure hydraulic conductivity (Reynolds & Elrick,

1990) was recently modified by using a multi-pressure head approach (SATURO, Meter Group Inc.) and was selected for use in this project.

2.2.2 | Measures of soil chemical properties

Crop growth responses to soil management are often indicated by measures of soil chemical properties, such as pH, electrical conductivity (EC), cation exchange capacity (CEC), and available soil nutrients (Corwin et al., 2003; Ghimire, Machado, & Bista, 2017; Maas & Grattan, 1999; Marschner, 2012). These measures of soil condition are a dynamic combination of inherent properties and management practices (e.g., CEC to clay and organic matter content).Therefore, while accurately assessing soil condition through measurement of chemical properties can be challenging, it is important because soil chemical conditions are known to regulate the abundance and availability of many of the nutrients necessary for crop growth, and therefore overall productivity (Marschner, 2012).

This interdependence is evident with nutrient availability because soil pH changes how nutrients interact with other constituents of the soil; therefore, soil pH constrains soil nutrient availability. An index of available soil nutrients was first obtained for this project by extracting nutrients using the Mehlich-3 method (Sikora & Moore, 2014). Then, pH measurements were used to trigger additional extractions. If the pH was >7.2, an ammonium acetate extraction was used to determine concentrations of K, Ca, Mg, and Na ions (Knudsen, Peterson, & Nelson, 1982). Also, if the pH was >7.2 for extraction of Fe, Zn, Cu, and Mn ions, a diethylenetriaminepentaacetic acid (DTPA) solution was used (Lindsay & Norvell, 1978). While the focus was on nutrients, the Mehlich-3 extracts were also analyzed for Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, S, Sr, and Zn concentrations (Sikora & Moore, 2014). As both CEC and base saturation are calculations based upon extractant concentrations (Sumner & Miller, 1996), they too are pH-dependent measurements, so when soil pH was below 7.2, Mehlich-3 results were used (Sikora & Moore, 2014); otherwise base saturation was based on an ammonium acetate extraction (Knudsen et al., 1982). A chemical indicator that is particularly relevant in warm arid regions, is sodium adsorption ratio (SAR), which is measured with inductively coupled plasma spectroscopy following saturated paste soil water extraction (Miller, Gavlak, & Horneck, 2013). Soils with high SAR values are prone to clay dispersion (Frenkel, Goertzen, & Rhoades, 1978), reduced infiltration (Suarez, Wood, & Lesch, 2008), and diminished aggregate stability (Rahimi, Pazira, & Tajik, 2000).

Soil nutrient analyses of P dynamics are inherently difficult to standardize because of variable fixation affinities of phosphate based on soil mineralogy and pH (Olsen & Sommers, 1982), as well as the relationships between plant uptake and phosphate-solubilizing microorganisms (Sharma, Sayyed, Trivedi, & Gobi, 2013). This study used the Mehlich-3 (Mehlich, 1984), modified Morgan's (Moebius-Clune et al., 2017), and H3A Haney (Haney et al., 2010) extraction methods for all samples, as well as the Olsen (sodium bicarbonate; Olsen, Cole, Watanabe, & Dean, 1954) extraction procedure when pH was >7.2. All extractions were quantified using inductively coupled plasma optical/atomic emission spectroscopy (ICP-OES or ICP-AES) (Olsen & Sommers, 1982; Sikora & Moore, 2014).

2.2.3 | Measures of soil biological processes

The C cycle in soils is an emergent property resulting from the activity of the biological community. Soil organisms feed on plant litter and root exudates to produce CO_2 and their activity also produces partially decomposed material and microbial waste products that persist in soils through physical or chemical stabilization (Cotrufo, Wallenstein, Boot, Denef, & Paul, 2013). The quantity of this diverse mixture of organic C compounds varies in native soils as a function of climate, soil texture, and topography (Burke et al., 1989). The most precise method to quantify soil C is dry combustion (Nelson & Sommers, 1996). There is broad agreement that cultivation decreases soil C (Post & Mann, 1990). Because of the tight linkage between soil C and other environmental benefits like increasing water holding capacity and infiltration, there is a strong interest in identifying the practices that increase soil organic C and soil health more broadly (Reicosky, 2003). However, there is considerable debate about what agronomic practices actually increase C in soils that have been intensively managed (e.g., Conant, Easter, Paustian, Swan, & Williams, 2007, Luo, Wang, & Sun, 2010).

While the pool of soil C reflects inherent site properties that vary at time scales of millennia (e.g., topography and soil texture), management and climate effects can vary soil properties at scales of years to decades. Hence pools and fluxes of C that vary at shorter time scales (e.g., labile or active fractions) can also be used to evaluate soil health and may be more sensitive to change in climate and management. Short-term soil incubation methodologies (i.e., respiration burst tests assessing the amount of CO_2 produced as a result of microbial activity following a rewetting event) were adopted in both the Haney Soil Test and the Cornell assessment. These specific approaches, performed under standardized conditions, provide insight into the availability of C and the activity of soil microbes (Zibilske, 1994). In addition, the permanganate oxidizable pool of C method developed by Weil, Islam, Stine, Gruver, and Samson-Liebig (2003) can detect differences in the labile soil C pool as a result of management (Culman et al., 2012).

Total N and C are tightly linked in soils, as indicated by the tight relationship between total C and N (Hartman &

Richardson, 2013). Like total C, dry combustion is commonly used to estimate the amount of total N in a soil (Nelson & Sommers, 1996). Total N is predominantly organic N, and microbial mineralization of this N is crucial for providing inorganic N (NO_3^-–N and NH_4^+–N), the predominant form of N available for plant uptake (Harmsen & Kolenbrander, 1965). Quantifying N mineralization in a soil using an anaerobic incubation method (Bundy & Meisinger, 1994) can estimate the capacity of a soil to supply N to plants.

An indirect approach to evaluating C and nutrient cycling in soils is quantifying extracellular enzyme activity. Instead of measuring fluxes or pools of C and nutrients directly, enzyme assays quantify the potential for reactions in the soil that are intimately associated with elemental cycling. For this project, the enzymes β-glucosidase, N-acetyl-β-D-glucosaminidase, phosphatase, and aryl sulfatase were selected as representative of the C, N, P, and S cycling, respectively. Standardized methods that measure potential enzyme activity using the same substrate, pH, temperature, and incubation length are employed to allow for comparisons across soil types (Acosta-Martinez & Tabatabai, 2011, Deng & Popova, 2011, Klose, Bilen, Tabatabai, & Dick, 2011, Tabatabai, 1994). Changes in enzyme activity have been linked to crop rotations, tillage, and fertilizer management (Acosta-Martinez et al., 2011, Chang, Chung, & Tsai, 2007, McDaniel & Grandy, 2016).

2.2.4 | Measures of soil microbiological communities

Increasing monocultures and agricultural intensification are known to lower soil microbial diversity and biomass relative to native systems (Niel, Tiemann, & Grandy, 2014; Tsiafouli et al., 2015); therefore, conventionally managed agricultural soils may have reductions in functionality. One measure of soil microbial community quantity and composition is the biomarker technique of phospholipid fatty acids (PLFAs) analysis. The PLFA method provides a measure of total microbial biomass, broad categorization of the bacterial community, and has the advantage of selecting for the active microbial community (Frostegård, Bååth, & Tunlid, 1993). Extraction and analysis of soil PLFAs has proved to be sensitive to identifying differences across a variety of ecosystem types (Brockett, Prescott, & Grayston, 2012; Hannam, Quideau, & Kishchuk, 2006); however, the method has shown to be both sensitive (Arcand, Helgason, & Lemke, 2016; Kiani et al., 2017) and insensitive (Helgason, Walley, & Germida, 2010) to long-term agricultural management practices. A review by Geisseler and Scow (2014) suggested further research on long-term agricultural studies to investigate effects of fertilizers on soil microbial communities in agricultural settings to address the mixed results. In a recent European-scale analysis of soil microbial communities, the PLFA technique was successful in differentiating land uses across bio-geographical regions (Francisco, Stone, Creamer, Sousa, & Morais, 2016). For this project, a miniaturized version of the standard Bligh–Dyer extraction procedure (Frostegård et al., 1993; Quideau et al., 2016) was selected to allow for greater throughput and cost optimization to handle the large sample numbers (Buyer & Sasser, 2012).

Currently, no widely accepted genomic indicators of agricultural soil health exist. This is primarily a result of a lack of readily available targeted amplicon and shotgun metagenomic sequence data from geographically diverse agricultural soils. However, recently published large-scale studies of environmental 16S ribosomal ribonucleic acid (16S rRNA) amplicon data have revealed significant statistical differences among land management practices in stream biofilm communities (Lear et al., 2013) and among soil environments in soil bacterial communities (Hermans et al., 2017). In forest ecosystems, changes in soil health due to compaction and organic matter removal resulted in significantly different soil microbial community structure (Hartmann et al., 2012) and the community's potential ability to decompose organic matter (Cardenas et al., 2015). Comparisons of management practices described above, combined with results from studies designed to track microbial community changes following implementation of agricultural management practices (e.g., Rieke, Soupir, Moorman, Yang, & Howe, 2018; Soman, Li, Wander, & Kent, 2017), lay the groundwork for applying genomic techniques to address broadscale soil health.

Three genomic tools were incorporated in NAPESHM to address this gap in knowledge; 16S rRNA amplicon sequencing, internal transcribed spacer (ITS) amplicon sequencing, and shotgun metagenomic sequencing. Soil DNA extraction, primer selection, library preparation, and sequencing amplification followed the Earth Microbiome Project protocols (Marotz et al., 2017; Thompson et al., 2017). Incorporation of targeted 16S rRNA (for archaea and bacteria) and ITS (for fungi) amplicon sequencing provides efficient identification and characterization of soil community members while the shotgun metagenomic sequencing complements microbial community analyses with functional genomic information.

2.2.5 | Integrative measures of soil physical, chemical, and biological properties

Proximal sensing techniques, such as visible and near-infrared (VisNIR) diffuse reflectance spectroscopy, provide a rapid, non-destructive method of indirectly measuring many soil properties simultaneously. Visible and near infrared spectroscopy primarily measures hydrogen and C bonding associated with silicate clays, and organic and inorganic C. Many properties associated with healthy soil are related to silicate clay and organic C interactions in soil. Previous literature has shown that VisNIR can be used to estimate several physical, chemical, and biological indicators of soil health (Veum, Goyne, Kremer, Miles, & Sudduth, 2014, 2015; Viscarra Rossel, McGlynn, & McBratney, 2006). Veum et al. (2014) used VisNIR to predict enzyme activity (dehydrogenase and phenol oxidase). This proximal sensing method is also strongly correlated with organic C, total N, and the biological Soil Management Assessment Framework score (Veum, Sudduth, Kremer, & Kitchen, 2015). Soil properties can also be estimated from VisNIR data collected in situ on soil surfaces and along soil profiles (Ackerson, Ge, & Morgan, 2017; Morgan, Waiser, Brown, & Hallmark, 2009).

2.3 | Site selection and locations

Teasing out the influence of inherent soil properties, climate, and management activities on soil condition requires a large collection of soil samples. To address this issue, the Soil Health Institute invited applications from investigators of long-term agricultural field experiments across North America (Partnering Scientists; Table 3) that were under continuous, monitored, replicated (when possible), management for 10 yr or more. Sites selected included six different soil orders of varying inherent properties and land management practices. Seven criteria were used to select sites to include in the study: (a) physical disturbance (e.g., tillage, erosion, or grazing); (b) cover crops (e.g., grains, legumes, or combinations); (c) crop diversity (e.g., crop rotation or pasture species diversity); (d) nutrient management (e.g., addition of different amendments); (e) water management; (f) geographical location and diversity; and (g) being part of national networks. In total, 120 long-term experimental sites from across North America were selected for the project (Table 3). Experiments ranged geographically from the northern Breton Plots site in Alberta, Canada (Dyck, Robertson, & Puurveen, 2012) to the southern Santo Domingo Yanhuitlán site in Oaxaca, Mexico (Fonteyne, 2017) and from the Pacific to the Atlantic Ocean (Figure 1).

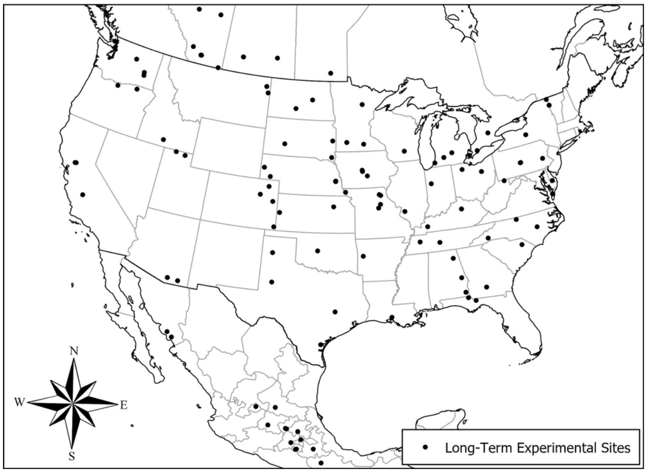

FIGURE 1 Geographical illustration of the 120 sites included as part of the North American Project to Evaluate Soil Health Measurements (NAPESHM).

2.4 | Sample collection

Plots, referred to as experimental units (EUs), were selected based on experimental treatment alignment with project criteria, regional relevance, and resource constraints. Further, efforts were made to ensure collection of site level replication when available; however, this was not possible for all sites (e.g., $n = 1$ for 90-yr-old Breton Plots and 131-yr-old Sanborn Field). At sites where all phases of a crop rotation were present, the priority was to sample the EUs where the dominant cash crop (e.g., corn [*Zea mays* L.] or spring wheat [*Triticum aestivum* L.]) would be harvested that season (i.e., transitioning out of fallow, green manure, etc.). For sites with cover crops, when possible, EUs selected had the cover crops terminated, but prior to tillage or other disturbance. Avoidance of tillage, fertilization, seeding, or any other plot level disturbance directly before sampling was a priority in collection of all EUs and was the driving reason for timely sample collection between spring thaw and summer planting at northern sites and during the dormant period between crops at southern sites. This target was achieved for all EUs collected in Canada, for 78% in Mexico, and 96% in USA; all remaining EUs were collected within the same growing season.

In each EU, a sharpshooter spade (38- by 15-cm blade) was used to create six (four when EUs were smaller than ∼30 m^2) 15- by 15-cm square holes located in a zigzag pattern across the EU (at least 1 m from the plot edge). The exception to this pattern occurred at three sites when Partnering Scientists identified specific locations to match where previous or ongoing studies were being sampled within the field. A soil knife was used to remove one slice of soil from three sides of each hole (one slice per untouched hole edge). Each slice was 4-cm wide and 1.5-cm thick to provide a uniform volume throughout the 15-cm depth sampled. These 18 subsamples were each placed in a labelled plastic bag for a single composite sample (bulk soil) and put in a cooler immediately after sampling. Care was taken to clean sampling equipment with ethanol or isopropyl alcohol between treatments with gloves being worn to prevent microbial cross-contamination. When there was variation in the field related to plant rows or beds, half of the samples were taken in row and half between rows. After sampling, the bulk soil sample was thoroughly mixed in a container that was sterilized with ethanol or isopropyl alcohol; and approximately 400 g of soil was homogenized after passing it through an 8-mm sieve. This subsample was then shipped in coolers with ice packs for arrival within 5 d

TABLE 3 The North American Project to Evaluate Soil Health Measurements Partnering Scientist Team includes representatives from 120 sites spread across three countries (Canada, CA; Mexico, MX; and the United States of America, USA). Here we identify each experimental site and its associated Partnering Scientist along with key features including the year of establishment, crop type (grain crop, vegetable, rangeland, or other), dominant soil order present, and the management practice of interest (physical disturbance, cover crops, crop diversity, nutrient management, and/or water management)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
Breton Plots	CA	Alberta	Univ. of Alberta	1929	M. Dyck	Alfisol	Grain crop	Nutrient management
Roy Berg Kinsella Research Ranch	CA	Alberta	Univ. of Alberta	1960	C. Carlyle	Mollisol	Rangeland	Physical disturbance
Stavely Research Ranch	CA	Alberta	Alberta Env. and Parks	1949	D. Bruhjell	Mollisol	Rangeland	Physical disturbance
Lethbridge Artificial Erosion Irrigated	CA	Alberta	AAFC	1990	F. Larney	Mollisol	Grain crop	Physical disturbance
Lethbridge Artificial Erosion Dryland	CA	Alberta	AAFC	1990	F. Larney	Mollisol	Grain crop	Physical disturbance
Lethbridge Long-Term Manure Plot	CA	Alberta	AAFC	1973	X. Hao	Mollisol	Grain crop	Nutrient management
Lethbridge Restorative Dryland Rotations	CA	Alberta	AAFC	1951	B. Ellert	Mollisol	Grain crop	Crop diversity
Lethbridge Cquest	CA	Alberta	AAFC	1993	C. Geddes	Mollisol	Grain crop	Nutrient management
Onefour Range Research Ranch	CA	Alberta	Alberta Env. and Parks	1928	D. Bruhjell	Mollisol	Rangeland	Crop diversity
Glenlea Long-Term Crop Rotation Study	CA	Manitoba	Univ. of Manitoba	1992	M. Entz	Vertisol	Grain crop	Crop diversity
Elora Long-Term Rotation Trial	CA	Ontario	Univ. of Guelph	1980	B. Deen	Alfisol	Grain crop	Crop diversity
Chemical fertilizer, various forms of pig manures and compost study	CA	Ontario	AAFC	2004	T. Zhang	Mollisol	Grain crop	Nutrient management
Great Lakes Water Quality Study	CA	Ontario	AAFC	2008	T. Zhang	Mollisol	Grain crop	Nutrient management, Water management
Ridgetown Long-Term Cover Crop Experiment	CA	Ontario	Univ. of Guelph	2007	L. Van Eerd	Alfisol	Vegetable	Cover crops
Swift Current OMC Study	CA	Saskatchewan	AAFC	1981	M. St. Luce	Mollisol	Grain crop	Physical disturbance, Crop diversity
Swift Current New Rotation	CA	Saskatchewan	AAFC	1987	M. St. Luce	Mollisol	Grain crop	Crop diversity
Indian Head Research Station	CA	Saskatchewan	AAFC	1957	W. May	Mollisol	Grain crop	Crop diversity
Pabellón de Arteaga, AGU	MX	Aguascalientes	INIFAP and CIMMTY	2011	D. Reyes, S. Fonteyne	Vertisol	Grain crop	Physical disturbance
Irapuato I, GTO	MX	Guanajuato	INIFAP and CIMMYT	2011	E. Moya, S. Fonteyne	Vertisol	Grain crop	Physical disturbance, Cover crops
Francisco I. Madero, HID	MX	Hidalgo	Universidad Politécnica de Francisco I. Madero and CIMMYT	2011	B. Lira, S. Fonteyne	Vertisol	Grain crop	Physical disturbance, Crop diversity

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
Metepec	MX	Mexico	CIMMYT	2014	N. Verhulst	Aridisol	Grain Crop	Physical disturbance, Cover crops
Texcoco I	MX	Mexico	CIMMYT	2013	N. Verhulst	Mollisol	Grain Crop	Physical disturbance, Cover crops
Texcoco II	MX	Mexico	CIMMYT	1999	N. Verhulst	Mollisol	Grain crop	Physical disturbance, Cover crops
Tlaltizapan de Zapata, MOR	MX	Morelos	CIMMYT	2011	O. Banuelos, S. Fonteyne	Vertisol	Grain crop	Physical disturbance, Cover crops
Zacatepec, MOR	MX	Morelos	INIFAP and CIMMYT	2012	A. Campos, S. Fonteyne	Vertisol	Grain crop	Physical disturbance, Cover crops, Crop diversity
Santo Domingo Yanhuitlán, OAX	MX	Oaxaca	INIFAP and CIMMYT	2012	L. Alcala, S. Fonteyne	Inceptisol	Grain crop	Physical disturbance
Molcaxac, PUE	MX	Puebla	CBTA 255	2011	A. Ramirez	Entisol	Grain crop	Physical disturbance, Cover crops, Crop diversity
San Juan del Río II, QTO	MX	Querétaro	INIFAP and CIMMYT	2012	D. Gutierrez, S. Fonteyne	Mollisol	Grain crop	Physical disturbance
San Juan del Río I, QTO	MX	Querétaro	SAQ and CIMMYT	2013	A. Solorio, S. Fonteyne	Mollisol	Grain crop	Physical disturbance, Cover crops, Crop diversity
Soledad de Graciano Sánchez, SLP	MX	San Luis Potosi	INIFAP and CIMMYT	1995	M. Gamiño, S. Fonteyne	Entisol	Grain crop	Physical disturbance, Cover crops
Navojoa, SON	MX	Sonora	INIFAP and CIMMYT	2011	J. Borbón, S. Fonteyne	Vertisol	Grain crop	Physical disturbance, Crop diversity
Cajeme I, SON	MX	Sonora	PIEAES - CIMMYT	2013	N. Verhulst	Vertisol	Grain crop	Physical disturbance, Crop diversity
Cajeme II, SON	MX	Sonora	CIMMYT	1992	N. Verhulst	Vertisol	Grain crop	Physical disturbance, Nutrient management, Cover crops
Sand Mountain Tillage Study	USA	Alabama	USDA-ARS-NSDL	1980	D. Watts	Ultisol	Grain crop	Physical disturbance, Crop diversity
Old Rotation	USA	Alabama	Auburn Univ.	1896	A. Gamble	Ultisol	Grain crop	Crop diversity
Sod-Based Rotation	USA	Alabama	Auburn Univ.	2001	A. Gamble	Ultisol	Other	Physical disturbance, Crop diversity
Sod-Based Rotation 2	USA	Alabama	Auburn Univ.	2001	A. Gamble	Ultisol	Other	Physical disturbance, Crop diversity

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
Santa Rita Experimental Range	USA	Arizona	Univ. of Arizona	1902	M. McClaran	Aridisol	Rangeland	Physical disturbance, Crop diversity
Walnut Gulch Experimental Watershed	USA	Arizona	USDA-ARS	1961	M. Kautz	Aridisol	Rangeland	Physical disturbance
Long-Term Effects of Grazing Management and Buffer Strips on Soils Fertilized with Poultry Litter	USA	Arkansas	USDA-ARS	2004	P. Moore	Ultisol	Rangeland	Physical disturbance, Crop diversity
Russell Ranch Wheat Systems	USA	California	Univ. of California-Davis	1993	K. Scow	Alfisol	Grain crop	Cover crop, Water management
Russell Ranch Tomato Systems	USA	California	Univ. of California-Davis	1993	K. Scow	Alfisol	Vegetable	Cover crop, Nutrient management
California Conservation Agriculture Systems National Research Initiative Study	USA	California	Univ. of California-Davis	1999	J. Mitchell	Aridisol	Vegetable	Physical disturbance, Cover crop
Walsh Dryland Agroecosystem Project	USA	Colorado	Colorado State Univ. and USDA-ARS	1985	M. Schipanski	Inceptisol	Grain crop	Crop diversity
Stratton Dryland Agroecosystem Project	USA	Colorado	Colorado State Univ. and USDA-ARS	1985	M. Schipanski	Mollisol	Grain crop	Crop diversity
Sterling Dryland Agroecosystem Project	USA	Colorado	Colorado State Univ. and USDA-ARS	1985	M. Schipanski	Mollisol	Grain crop	Crop diversity
USDA-ARS Central Plains Experimental Range Long-Term Grazing Intensity	USA	Colorado	USDA-ARS	1939	J. Derner	Aridisol	Rangeland	Physical disturbance
USDA-ARS Central Plains Experimental Range Collaborative Adaptive Rangeland Management	USA	Colorado	USDA-ARS	2014	J. Derner	Aridisol	Rangeland	Physical disturbance
Byers Colorado Long-Term Fertilizer/Biosolids Site	USA	Colorado	Colorado State Univ.	1999	J. Ippolito	Mollisol	Grain crop	Nutrient management
UD Long-Term P Application	USA	Delaware	Univ. of Delaware	2000	A. Shober	Ultisol	Grain crop	Nutrient management
Marianna/Sod-Based Rotation	USA	Florida	Univ. of Florida and Auburn Univ.	2002	D. Wright	Ultisol	Grain crop	Crop diversity
NFREC Sod-Based Rotation	USA	Florida	Univ. of Florida	1999	D. Wright	Ultisol	Grain crop	Crop diversity
RDC Pivot	USA	Georgia	Univ. of Georgia	1997	J. Paulk	Ultisol	Grain crop	Physical disturbance
Kimberly Long-Term Manure Application Study	USA	Idaho	USDA-ARS	2012	R. Dungan	Aridisol	Grain crop	Nutrient management

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
SIU Long-Term Tillage by Fertility Trial	USA	Illinois	Southern Illinois Univ.	1970	A. Sadeghpour	Alfisol	Grain crop	Physical disturbance, Nutrient management
Purdue Long-Term Tillage and Rotation Plots	USA	Indiana	Purdue Univ.	1975	T. Vyn	Mollisol	Grain crop	Physical disturbance, Crop diversity, Nutrient management
Prairie Strips at Neal Smith National Wildlife Refuge	USA	Iowa	U.S. Fish and Wildlife	2007	M. Helmers	Alfisol	Grain crop	Crop diversity
Comparison of Biofuel Systems	USA	Iowa	Iowa State Univ.	2008	M. Thompson	Mollisol	Grain crop	Crop diversity, Nutrient management
Marsden Farm Cropping Systems Experiment	USA	Iowa	Iowa State Univ.	2001	M. Liebman	Mollisol	Grain crop	Crop diversity
Intensifying a No-Till Wheat-Sorghum-Soybean Rotation with Double-Crops and Cover Crops	USA	Kansas	Kansas State Univ.	2007	K. Roozeboom	Mollisol	Grain crop	Cover crop, Nutrient management
Tillage Intensity Study	USA	Kansas	Kansas State Univ.	1988	A. Schlegel	Mollisol	Grain crop	Physical disturbance
UKREC Long-Term Tillage Trial	USA	Kentucky	Univ. of Kentucky	1992	E. Ritchey	Alfisol	Grain crop	Physical disturbance
Grove F05	USA	Kentucky	Univ. of Kentucky	1986	J. Grove	Alfisol	Grain crop	Crop diversity, Nutrient management
Blevins-Grove Long-Term Tillage Trial	USA	Kentucky	Univ. of Kentucky	1970	H. Poffenbarger	Alfisol	Grain crop	Physical disturbance, Nutrient management
Long-Term Sugarcane Residue Management Study	USA	Louisiana	Louisiana State Univ.	1996	L. Fultz	Mollisol	Other	Cover crop
Horticulture Research and Education Center - HF3 Long-Term Organic Reduced Tillage Trial	USA	Michigan	Michigan State Univ.	2009	D. Brainard	Alfisol	Vegetable	Physical disturbance, Nutrient management
South West Michigan Research and Extension Center	USA	Michigan	Michigan State Univ.	2008	Z. Hayden	Entisol	Vegetable	Physical disturbance, Cover crop, Crop diversity
Biodiversity Gradient Experiment at Kellogg Biological Station, Long-Term Ecological Research	USA	Michigan	Michigan State Univ.	2000	S. Hamilton	Alfisol	Grain crop	Crop diversity
Main Cropping System Experiment at Kellogg Biological Station, Long-Term Ecological Research	USA	Michigan	Michigan State Univ.	1988	N. Millar	Alfisol	Grain crop	Physical disturbance, Crop diversity, Nutrient management

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
Minnesota Long-Term Agricultural Research Network - Grand Rapids	USA	Minnesota	Univ. of Minnesota	2014	G. Johnson	Alfisol	Grain crop	Crop diversity, Cover crop
Minnesota Long-Term Agricultural Research Network - Lamberton	USA	Minnesota	Univ. of Minnesota	2014	G. Johnson	Mollisol	Grain crop	Cover crop, Crop diversity
Long-Term Tillage Trial	USA	Minnesota	Univ. of Minnesota	1986	J. Strock	Mollisol	Grain crop	Physical disturbance
Minnesota Long-Term Agricultural Research Network - Wasesa	USA	Minnesota	Univ. of Minnesota	2014	G. Johnson	Mollisol	Grain crop	Cover crop, Crop diversity
Centralia Missouri Cropping System Research Site	USA	Missouri	USDA-ARS and Univ. of Missouri	1991	N. Kitchen	Alfisol	Grain crop	Physical disturbance, Crop diversity
Sanborn Field	USA	Missouri	Univ. of Missouri	1888	T. Reinbott	Alfisol	Grain crop	Physical disturbance, Crop diversity
Graves-Chapple Research Center – Long-Term Tillage Comparison	USA	Missouri	Univ. of Missouri	1988	J. Crawford	Mollisol	Grain crop	Physical disturbance
MU Drainage and Sub-irrigation Research	USA	Missouri	Univ. of Missouri	2001	K. Nelson	Alfisol	Grain crop	Water management
Tillage and Cover Crop Management Systems	USA	Missouri	Univ. of Missouri	1994	K. Nelson	Alfisol	Grain crop	Physical disturbance, Cover crop, Crop diversity
GRACEnet	USA	Montana	USDA-ARS	2005	U. Sainju	Mollisol	Grain crop	Crop diversity, Nutrient management
Agronomics	USA	Montana	USDA-ARS	1983	U. Sainju	Mollisol	Grain crop	Crop diversity
Platte River High Plains Aquifer	USA	Nebraska	PRHPA-LTAR	2001	A. Suyker	Mollisol	Grain crop	Physical disturbance, Crop diversity, Nutrient management
HPAL Long-Term Soil Management Tillage Study	USA	Nebraska	Univ. of Nebraska	1970	C. Creech	Mollisol	Grain crop	Physical disturbance
Knorr-Holden	USA	Nebraska	Univ. of Nebraska	1912	B. Maharjan	Mollisol	Grain crop	Nutrient management
Chazy Tillage Plots	USA	New York	Miner Institute	1973	B. Schindelbeck	Inceptisol	Grain crop	Physical disturbance, Cover crop
Willsboro Farm Drainage Plots-Sand	USA	New York	Cornell Univ.	1993	B. Schindelbeck	Entisol	Grain crop	Physical disturbance
Willsboro Farm Drainage Plots- Clay	USA	New York	Cornell Univ.	1993	B. Schindelbeck	Alfisol	Grain crop	Physical disturbance
Musgrave Tillage Plots	USA	New York	Cornell Univ.	1993	K. Kurtz	Alfisol	Grain crop	Physical disturbance, Cover crop
Mills River Study	USA	North Carolina	North Carolina State Univ. and NCDA&CS	1994	D. Osmond	Ultisol	Grain crop	Physical disturbance, Nutrient management

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
Reidsville Tillage Trial	USA	North Carolina	North Carolina State Univ. and NCDA&CS	1984	J. Heitman	Ultisol	Grain crop	Physical disturbance
CEFS Farming Systems Research Unit	USA	North Carolina	North Carolina Department of Agriculture	1998	A. Franzluebbers	Ultisol	Grain crop	Physical disturbance, Crop diversity, Nutrient management
Soil Quality Management Study	USA	North Dakota	USDA-ARS	1993	M. Liebig	Mollisol	Grain crop	Crop diversity
CREC Long-Term Cropping Systems Study	USA	North Dakota	North Dakota State Univ.	1987	E. Aberle	Mollisol	Grain crop	Physical disturbance, Nutrient management
Northwest OARDC No-Till and Rotation Plot	USA	Ohio	Ohio State Univ.	1963	S. Culman	Alfisol	Grain crop	Physical disturbance, Crop diversity
Wooster Long-Term No-Till Trial	USA	Ohio	Ohio State Univ.	1962	S. Culman	Alfisol	Grain crop	Physical disturbance, Crop diversity
The Water Resources and Erosion Watersheds	USA	Oklahoma	USDA-ARS	1976	A. Fortuna	Mollisol	Grain crop	Physical disturbance, Crop diversity
Columbia Basin Agricultural Research Center - Winter Wheat	USA	Oregon	Oregon State Univ.	2003	S. Machado	Mollisol	Grain crop	Physical disturbance, Cover crop
Columbia Basin Agricultural Research Center - Wheat, Peas	USA	Oregon	Oregon State Univ.	1963	S. Machado	Mollisol	Grain crop	Physical disturbance, Crop diversity
Columbia Basin Agricultural Research Center – Residue Management	USA	Oregon	Oregon State Univ.	1931	S. Machado	Mollisol	Grain crop	Physical disturbance, Nutrient management
Farming Systems Trial	USA	Pennsylvania	Rodale Institute	1981	E. Omondi	Alfisol	Grain crop	Physical disturbance, Cover crop, Crop diversity, Nutrient management
Penn State Long-Term Tillage Trial	USA	Pennsylvania	Penn State Univ.	1978	S. Duiker	Alfisol	Grain crop	Physical disturbance
Sustainable Dairy Cropping Systems Project	USA	Pennsylvania	USDA-ARS and Penn State Univ.	2010	C. Dell	Ultisol	Grain crop	Crop diversity, Nutrient management
ARS-USDA Long-Term Conservation Tillage DOE Plots	USA	South Carolina	USDA-ARS	1979	T. Ducey	Ultisol	Grain crop	Physical disturbance, Cover crops
SDSU Southeast Research Farm	USA	South Dakota	South Dakota State Univ.	1991	S. Kumar	Mollisol	Grain crop	Physical disturbance, Cover crops
SDaltrot	USA	South Dakota	USDA-ARS	2000	S. Osborne	Mollisol	Grain crop	Crop diversity, Cover crops

(Continues)

TABLE 3 (Continued)

Site name	Country	State/Province	Affiliation[a]	Year established	Primary contact	Soil order	Crop type	Management practice of interest
SDSU Cottonwood Research Station/Long-Term Grazing Study	USA	South Dakota	South Dakota State Univ.	1907	K. Cammack	Inceptisol	Rangeland	Physical disturbance
UTIA RECM/Systems Study	USA	Tennessee	Univ. of Tennessee	2001	V. Sykes	Alfisol	Grain crop	Crop diversity, Cover crops
UTIA MTREC/Systems Study	USA	Tennessee	Univ. of Tennessee	2001	V. Sykes	Alfisol	Grain crop	Crop diversity, Cover crops
Graded Terraces - Soil & Water Conservation	USA	Texas	USDA-ARS	1949	R. L. Baumhardt	Mollisol	Grain crop	Physical disturbance, Crop diversity
AG-CARES Long-Term Tillage	USA	Texas	Texas A&M Univ.	1998	K. Lewis	Alfisol	Grain crop	Physical disturbance, Cover crops
Sorghum and Cotton No-Till vs Conventional Till at Corpus Christi	USA	Texas	Texas A&M Univ.	2008	J. Foster	Vertisol	Grain crop	Physical disturbance, Crop diversity
Central Texas Tillage Rotation and Fertility Study	USA	Texas	Texas A&M Univ.	1982	J. Howe	Inceptisol	Grain crop	Physical disturbance, Crop diversity, Nutrient management
Snowville Historic Plots	USA	Utah	Private owner	1994	J. Reeve	Inceptisol	Grain crop	Nutrient management
Greenville Organic Rotation Study	USA	Utah	Utah State Univ.	2008	J. Reeve	Mollisol	Vegetable	Nutrient management, Crop diversity, Cover crop
Long-Term Poultry Litter Rotation	USA	Virginia	Virginia Tech	2003	M. Reiter	Ultisol	Grain crop	Nutrient management
Long-Term Biosolids Research Plots, GP-17	USA	Washington	Washington State Univ.	1994	A. Bary	Mollisol	Grain crop	Nutrient management
Jirava Long-Term Cropping Systems Study	USA	Washington	Washington State Univ.	1997	W. Schillinger	Mollisol	Grain crop	Physical disturbance, Crop diversity
No-till/Conventional Tillage Integrated Cropping Systems Research Project	USA	Washington	Washington State Univ.	1995	H. Tao	Mollisol	Grain crop	Physical disturbance, Crop diversity
Organic Crop Livestock Systems Experiment	USA	West Virginia	West Virginia Univ.	1999	E. Pena-Yewtukhiw	Alfisol	Rangeland	Crop diversity, Nutrient management, grazing
The Wisconsin Integrated Cropping Systems Trial	USA	Wisconsin	Univ. of Wisconsin	1989	G. Sanford	Mollisol	Grain crop	Crop diversity, Cover crop, Nutrient management
USDA-ARS Cheyenne, WY Long-Term Stocking Rate	USA	Wyoming	USDA-ARS	1982	J. Derner	Mollisol	Rangeland	Physical disturbance

[a] AAFC, Agriculture and Agri-Food Canada; INIFAP, Instituto Nacional de Investigaciones Forestales, Agricolas y Pecuarias; CIMMYT, Centro International de Mejoramiento de Maiz y Trigo; CBTA, Centro de Bachillerato Tecnoogico Agropecuario; SAQ, Sustentabilidad Agropecuaria de Queretaro; NCDA&CS, North Carolina Department of Agriculture and Consumer Services; PIEAES, Patronato para la Investigación y Experimentación AgrÍcola del Estado de Sonora; USDA-ARS NSDL, United States Department of Agriculture Agricultural Research Service National Soils Dynamic Lab; USDA-ARS, United States Department of Agriculture Agricultural Research Service; PRHPA-LTAR, Platte River High Plains Aquifer-Long Term Agricultural Research.

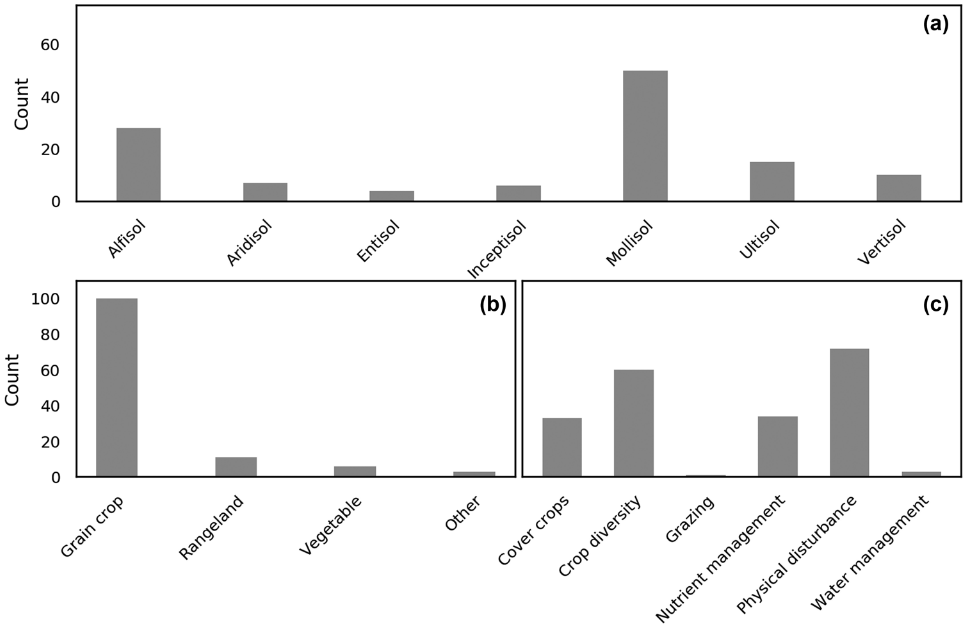

FIGURE 2 Frequency counts of soil order, crop type, and management practice of interest included in the North American Project to Evaluate Soil Health Measurements

to the analytical laboratories for genomic, PLFA, enzyme, and Haney Soil Test analyses. The remaining 2.5 kg of soil sample was split and shipped to other analytical laboratories to arrive within a week of collection.

Near four of the sampling holes in each EU, a 7.6-cm diam., 7.6-cm deep bulk density core was collected by driving a metal or plastic core into the mineral soil surface. Two of these cores (plastic) were preserved intact for measuring the soil-held water at field capacity (–33 kPa), while the remaining two (metal) were combined for a dried mass bulk density measurement. Again, when rows or beds were present, half of the cores were taken in row and half between rows. Once on each EU, a SATURO device (Meter Group) was used to measure K_{fs}. When rows were present this device was placed within the plant row or bed.

3 | SUMMARY OF SOIL COLLECTION

The first objective of the NAPESHM project was achieved through its amassing a comprehensive agricultural soil collection. The NAPESHM EU soil archive is comprised of 2029 soil samples from long-term experimental sites which captured a range of climates (Figure 1), management practices (Figure 2), and inherent soil properties (Figure 3). The sites were spread across a large geographic area representing spatially diverse growing conditions from mean annual temperature and precipitation of 5.8 °C and 384 mm at the Breton Plots (Dyck et al., 2012) to 17.5 °C and 827 mm in Santo Domingo Yanhuitlán (Thornton et al., 2018). As would be expected from an agricultural project, Mollisols were present for more than 45% of the 120 sites. However, another 6 of the

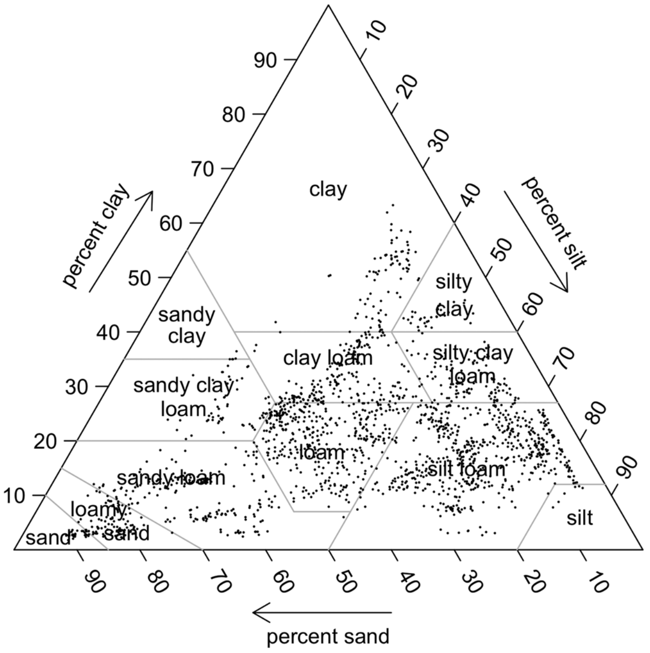

FIGURE 3 Particle size analysis results for 1722 of 2029 soil samples collected 0–15-cm deep as part of the North American Project to Evaluate Soil Health Measurements

12 soil orders in U.S. Taxonomy are represented in the project. Sites with grain crops were the most common, but vegetable crops and grazing operations were also sampled. More than 56% of the sites were in row-crop or drilled grain production (Figure 2). Of greatest interest was the captured diversity of particle size distribution among the EUs (Figure 3)–an inherent soil property believed to be determinant of the extent that management impacts soil health.

4 | OUTLOOK

This project will report baseline data on the influence of pedogenesis, location, climate, and management history on soil health. In addition, the project will determine the utility and sensitivity of more established and newer soil health indicators and soil health evaluation programs for their ability to distinguish differences in soil health. The ultimate goal is to develop the definitive, comprehensive soil health evaluation program for North America, including its individual component soil health measures, associated protocols, and interpretations.

To best assess the results of management practices on our agricultural soil resource, we must first be able to correctly interpret how land management practices are affecting soil health. The evaluation of 28 indicators across 120 experimental sites in North America is expected to provide the data for decision-making that supports effective soil health management practices. As mentioned above, the first objective of the project to build a soil archive was achieved through collection of 1906 of the total 2029 EUs within 6 mo of forming the project team. The remaining samples were collected within 10 mo. These latter collections will be compared to adjacent sites collected earlier in the year. If any of this subset is determined to be significantly different in soil condition to the main collection, the data will be used for validation of results from the main data set for collections at different times of the year. Second, laboratory analyses for all measurements (except genomics) of all samples will be complete within a year of starting the field campaign. Data analysis will follow with presentations and publications of the results commencing within 2 yr of initiating the research team.

Through this analysis, we plan to integrate data because we expect insight to come from combining soil measures in ways that address various aspects of soil health rather than of segregating soil properties into discrete units related to physics, chemistry, and biology. Instead of relying on individual properties, soil health indicators can be aggregated in ways that relate to soil functions. For example, the abiotic property of texture impacts the inherent ability of a soil to store water. However, biotic properties, such as total organic matter, have been known to increase available water holding capacity (AWHC) by as much as 50% for each 1% increase in organic matter (Hudson, 1994). Additionally, aggregate stability and the distribution of aggregate sizes influence AWHC and are influenced by bacterial exudates that glue particles together, fungal hyphae and roots that push and hold them, chemical bonding patterns of various nutrients, and whether or not the soil has been physically disturbed. By focusing on the measurements, or indicators, that describe each function we can start to answer specific questions posed by various stakeholders, such as how does a cover crop, compared to other soil health promoting practices, affect the ability of soil to store and deliver water to the next crop?

Beyond the overall goal of the project, more specific paths of discovery will also be pursued using the data. For example, in soil hydrology, we will have paired measures (treatment and control) of K_{fs}, AWHC, and bulk density to develop pedotransfer functions necessary for hydrology models that quantify off-farm ecosystem services of water quality and quantity. In addition, we will seek to identify subsets of microbial genera that are abundant, easily detected, and related to functional genes and soil health measures. If identified, these genera may help link microbial communities to soil functions.

ACKNOWLEDGEMENTS

The NAPESHM project is part of a broader effort titled, “Assessing and Expanding Soil Health for Production, Economic, and Environmental Benefits”. The project is funded by the Foundation for Food and Agricultural Research (grant ID 523926), General Mills, and the Samuel Roberts Noble Foundation. The project is a partnership among the Soil Health Institute, the Soil Health Partnership, and The Nature Conservancy. Profound gratitude is extended to each member of our Partnering Scientists team identified in Table 3. Partnering Scientists provided site access, sampling support (labor), and site history information. Many of these scientists continue to provide support in analyses, interpretations, and in other ways. Thank You!

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Charlotte E. Norris https://orcid.org/0000-0002-6372-9902
G. Mac Bean https://orcid.org/0000-0002-2206-3171
Shannon B. Cappellazzi https://orcid.org/0000-0001-7249-9494
Michael Cope https://orcid.org/0000-0001-9398-2936
Kelsey L.H. Greub https://orcid.org/0000-0003-0450-9077
Daniel Liptzin https://orcid.org/0000-0002-8243-267X
Elizabeth L. Rieke https://orcid.org/0000-0003-2287-3884
Cristine L.S. Morgan https://orcid.org/0000-0001-9836-0669

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How to cite this article: Norris CE, Bean GM, Cappellazzi SB, et al. Introducing the North American project to evaluate soil health measurements. *Agronomy Journal*. 2020;112:3195–3215. https://doi.org/10.1002/agj2.20234