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Developments in Agricultural Soil Quality and Health: Reflections by the Research Committee on Soil Organic Matter Management

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The North Central Education and Research Activity Committee (NCERA-59) was formed in 1952 to address how soil organic matter formation and management practices affect soil structure and productivity. It is in this capacity that we comment on the science supporting soil quality and associated soil health assessment for agricultural lands with the goal of hastening progress in this important field. Even though the suite of soil quality indicators being applied by U.S. soil health efforts closely mirrors the "minimum data set" we developed and recommended in the mid-1990s, we question whether the methods or means for their selection and development are sufficient to meet current and emerging soil health challenges. The rush to enshrine a standard suite of dated measures may be incompatible with longer-term goals. Legitimate study of soil health considers soil change accrued over years to decades that influence on- and off-site function. Tailoring of methods to local conditions is needed to effectively apply and interpret indicators for different soil resource regions and land uses. Adherence to a set suite of methods selected by subjective criteria should be avoided, particularly when we do not yet have adequate data or agreed upon interpretive frameworks for many so-called "Tier 1" biological indicators used in soil health assessment. While pooling data collected by producer-groups is one of the most exciting new trends in soil health, standardizing methods to meet broad inventory goals could compromise indicator use for site or application-specific problem solving. Changes in our nation's research landscape are shifting responsibility for soil stewardship from national and state government backed entities to public-private partnerships. As a result, it is critical to ensure that the data needed to assess soil health are generated by reproducible methods selected through a transparent process, and that data are readily available for public and private sector use. Appropriate methods for engagement need to be applied by public-private research partnerships as they establish and expand coordinated research enterprises that can deliver fact-based interpretation of soil quality indicators within the type of normative soil health framework conceived by USDA over 20 years ago. We look to existing examples as we consider how to put soil health information into the hands of practitioners in a manner that protects soils' services.

Keywords: soil quality, soil health, soil services, indicators, frameworks, public-private partnerships (PPP), privatization, open source data

BACKGROUND AND HISTORY

The North Central Education and Research Activity Committee (NCERA)-59 is a multi-state research and extension committee first formed in 1952 to address questions about how organic matter formation and management influence soil structure and productivity (Allan et al., 2006). The committee's activities are supported by U.S. federal dollars provided to Land-Grant Universities (LGUs) and State Agricultural Experiment Stations (SAES) for work to address research topics of high-priority to states (SAED, 2013). Throughout its history NCERA-59 has concentrated investigations on how management practices affect the nature and genesis of soil organic matter and how this alters soils' biological, physical, and chemical functions. Past accomplishments that include Soil Science Society of America (SSSA) publications "Defining Soil Quality for a Sustainable Environment" (Doran et al., 1994) and "Methods for Assessing Soil Quality" (Doran and Jones, 1996) were completed in collaboration with partners from the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) and Natural Resources Conservation Service (NRCS). Committee activities have informed efforts led by the NRCS Science and Technology (STD) and Soil Health Divisions (SHD), and Dynamic Soil Property (DSP) Technical Team (e.g., see NRCS, 2014 DSP Inventory and Assessment Long-Term Plan 2014–2016). These, and the SHD efforts to popularize soil quality concepts through their "Unlocking the Secrets of the Soil" campaign (Nichols, 2014) have all helped to shape the current U.S. soil health discourse. Today's soil health programs are firmly rooted in the efforts of members of NCERA-59 and others, including SSSA Soil Quality and Soil Change working groups, who decided 20 years ago to emphasize soil quality as a functional research idea. The Committee has, and continues to seek the global exchange of ideas between researchers and practitioners engaged in soil quality indicator development for resource inventory and soil health applications.

The U.S. discourse on soil health assessment is also being shaped by privatization of agricultural research driven by declining public support for agricultural research (Friedman, 2016; Lusk, 2016). While this trend has accelerated in the past 3 years, it has been ongoing for decades. Public financial support, which had covered at least half of total research costs for food and agriculturally related research globally until the mid-1980s, now covers <30% of total costs while private support covers the rest in the U.S. and abroad (Clancey et al., 2016; Heisey and Fuglie, 2018). Increased reliance of public institutions on private funding, and operation of the institutions in a businesslike manner has also been a global phenomenon (Holzhacker et al., 2009). Despite this shift, and the consolidation in funding in the U.S. that has moved federal dollars away from research and extension committees, Land Grant Universities and SAES to federally administered competitive grants programs (Huffman et al., 2006; SAED, 2013), NCERA-59 continues to build on its legacy. NCERA-59 contributes to the science of soil quality and soil health by integrating research and extension to foster data-based practices to increase our understanding of the soil's capacity to function and provide soil services. We know that coordinated regional-research efforts can provide an effective way to advance the Land Grant University mission to support agriculture that promotes economic development while achieving sustainability goals (Labarthe and Laurent, 2013; Pardey et al., 2013).

Ganning et al. (2012) suggest that public universities reorient their facilities to become "regional resources for a new era of agricultural development" achieved through community—university partnerships. To do this public universities need successful models for Public-Private partnerships that enhance innovation through knowledge exchange (Ankrah and Tabbaa, 2015). We must look for proven examples of how public-private research partnerships such as the Soil Health Institute (SHI), a private-nonprofit research entity initiated by the Samuel Roberts Noble Foundation and the Farm Foundation (Stott, 2018), can best contribute to soil health efforts in partnership with existing efforts to advance the public's soil health agenda. In 2017 the SHI and key partners (the Nature Conservancy and the Soil Health Partnership), received $20M to advance soil health goals. One half of the funds were provided as "matching funds" by General Mills, Walmart, and the Walton Foundation, with the remaining half provided by USDA through the Foundation for Food and Agriculture Research (FFAR), a public-nonprofit established by the 2014 Farm Bill (USDA, 2014). Together the Nobel Foundation and SHI are seeking additional FFAR funds to help launch an ecosystem services market to monetize soil health.

The U.S. experience reflects a global shift to market-based approaches to agricultural research and development to achieve sustainable development goals. Privatization of University research and natural resource management began in the 1980s in Australia and New Zealand with the belief that public-private partnerships would provide a cost-effective approach to effecting change (Curtis et al., 2014). That premise underpins UN Global Compact Food and Agriculture Business Principles (FABs) and its Principles for Sustainable Soil Management that assert "the most complex soil management issues are best addressed through strong public–private partnerships' (UNGC, 2016). We hope FAB principles that outline how companies engage with governments, civil society and other stakeholders can be successfully implemented in our U.S. soil health experiment but worry as we look at the Australia and New Zealand example. Despite their use of community-based approaches that apply a mix of market-based processes and external interventions to enhance public benefits (Hodge and Adams, 2014) critics argue efforts have not achieved environmental goals and have privileged industry while transferring both risk and costs to future generations (Baldwin et al., 2019). Here we reflect on the U.S. soil health privatization experiment and, ask how do public and professional societies and national, regional, state, and local institutions work with the private sector to best marshal our efforts and resources to promote soil health as a public good?

TERMS, FRAMEWORKS AND INDICATORS

To answer the above question, we might ask whether participants in the soil health discourse have a shared understanding and common goals. At present, a bewildering panoply of different terms is being used to relate soil-based information to actions and outcomes. While the terms are related, it may not be helpful that the two distinct terms "soil quality" and "soil health" are commonly used interchangeably. In the U.S. the term "soil quality" typically refers to the status of soil properties that underpin soils' capacities to support key functions (e.g., promote healthy plant and animal growth, filter and retain water and nutrients, and resist and recover from degradative processes; Doran et al., 1994; Andrews et al., 2004; Karlen et al., 2013). Related efforts have tended to be agriculturally focused as they sought to identify indicators that are useful proxies for soil function, in which functionality is defined based on the context, or soil system, and the soil processes occurring within it determine soils' ability to provide services (see Hewett et al., 2015; Bunemann et al., 2018 and references therein). "Soil services" refers to ecosystem services provided by soils that closely parallel "outcomes" of management (e.g., enhanced productivity, water quality and quantity, reduced erosion) scored in some NRCS assessment tools (Ugarte and Wander, 2013). When soil-related ecosystem services are included in global discussions regarding soil degradation (IPBES, 2018), change in ecosystem services over time (Robinson et al., 2013), security of soils and soil-related ecosystem services (Florinsky, 2012; McBratney et al., 2014) and global threats to soils (FAO and ITPS, 2015; IPBES, 2019) they are often presented in terms of "natural capital", as indicator stocks or process rates ideally aligned with soil services or functions[1] (Robinson et al., 2009; Dominati et al., 2010). While recognizing that the terminology and organizational frameworks describing soil services have and will continue to evolve with this important conversation (Baveye et al., 2016), the Committee encourages the use of terms that are consistent with the rest of the Americas, Europe, Asia and Australia to define processes, functions and services (Robinson et al., 2009; Dominati et al., 2010; Braat and de Groot, 2012; IPBES, 2018) even as we recognize that simplifications are likely to be needed for practitioner uptake and logical consistency (see Baveye et al., 2016 for a useful discussion). We also propose to use the term "soil quality" to describe soil status with raw, unscaled indicators and "soil health" to provide the valuation of a soils' functional status in relation to soil services (**Figure 1**). *More succinctly, soil quality defines the characteristics and dynamics of soil properties, while soil health defines function in terms of a given soil's capacity to supply a service based on the existing stock or process.* This approach is compatible with common frameworks for indicator assessment, including State and Transition Models (STMs) or adaptations thereof (e.g., Robinson et al., 2013; Bunemann et al., 2018) that have been used in the US for resource inventory and internationally to organize and communicate information regarding ecosystem change (FAO and ITPS, 2015). By clearly defining the site and system context within a carefully articulated normative frame that defines the scope, application, and desired services for soil quality indicators, one can develop meaningful, scientifically based frameworks for soil health assessment. Viable frameworks will apply a multi-step process that first makes a clear distinction between measured properties (soil quality indicators) comprised of non-subjective values measured using appropriate and reproducible methods to link indicator status to functions *before* conducting soil health assessment using accepted and reproducible methods to assign values. While the steps involved in this were clearly outlined by Andrews et al. (2004) in the Soil Management Assessment Framework (SMAF) and have been recently recast by Rinot et al. (2018), very few efforts have used quantitative, reproducible, and statistically valid methods to overcome challenges associated with the subjective aspects of indicator interpretation and scoring raised by Sojka and Upchurch (1999) and Sojka et al. (2003) in the U.S. that continue to pose a challenge in the U.S. and elsewhere where stakeholder interests and goals clash. A common approach or at least shared understanding of the terms and methods being used to assign value for soil services is needed for market-backed solutions to sustainable development to be taken seriously.

Sustainable business practices endorsed by FABs previously mentioned suggest differences between individual and societal valuation might be achieved using clearly articulated procedures along with formalized methods for multi-stakeholder standards development (for example ISO 14040) to devise interpretive scores relating soil quality to soil services (**Figure 1**). However, work by Baveye et al. (2016) points out that while participatory multi-criteria decision analysis tools can assign value to services where relationships are established, which is rare and typically exist only for extractive services, such tools will not likely overcome challenges associated with the assignment of abstract cultural, aesthetic or intrinsic values when used to develop

[1] Available online at: http://millenniumassessment.org/en/index (accessed December 31, 2018).

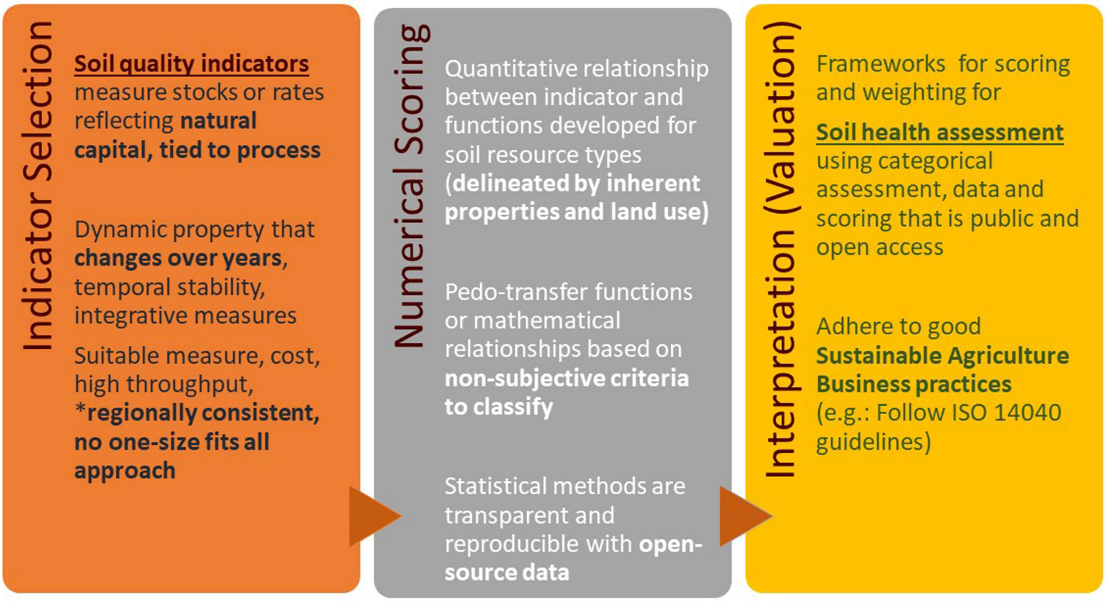

FIGURE 1 | Steps in the use of soil quality indicators within soil health frameworks.

market based systems because the replacement value of soils is unfathomably large particularly when considered at broad scales. Critiques of market-focused frameworks applying multi-stakeholder methods suggest clearer definitions of public benefit or public interest may help avoid common pitfalls which include the privileging of industries through legislation and incentives, light-handed regulation, and weak laws that fail to address public concern about negative impacts, and lack of transparency in decision making (Hudgins and Poole, 2014; Baldwin et al., 2019).

Research is needed on multiple fronts to begin to understand how to advance goals as complex as soil protection, security or stewardship through public-private partnerships that develop and apply multi-stakeholder frameworks.

Our Committee and other agronomically-oriented soil health assessment efforts have historically focused largely on developing indicators that provide integrative measures of soil biology, biochemistry, and soil physical structure to fill a gap in assessment left by traditional soil testing and survey efforts. Appropriate soil quality indicators include properties or processes that change in response to land use practices over timescales of years or decades. This means that soil tests used to guide amendment practices that can alter properties over days or months are not featured soil quality measures even though they provide essential information about soil's capacity to support plant growth. The pressure to treat soil quality and fertility as synonyms within a commercialized soil health setting must be resisted to protect the public's interest in soil services. Biotic or physical indicators that change too rapidly to be useful for soil taxonomy (Tugel et al., 2005) have been prioritized as indicators due to the assumption that the abundance, composition and/or activity of indicators significantly influences the agronomic efficiency and long-term productivity of soil-based agroecosystems. An accompanying assumption is that gains in efficiency, resistance and resilience increase with investment in below-ground productivity and biological associations (Wander, 2009; Schmidt et al., 2015). Recent European critiques of the soil health concept also focus on the biological and bio-physicochemical dimensions of soil health (Bunemann et al., 2018; Rinot et al., 2018). Unfortunately, many of the biological mechanisms and feedbacks thought to regulate processes and ultimately deliver soil services supplied by intact soils are neither adequately understood nor clearly related to indicators one might measure in a soil sample taken from the field. Fortunately improving methods and a growing literature are providing fundamental insights into root-soil-microbe-interactions and the mechanisms controlling soil services within agronomic settings (Mothapo et al., 2015; Jeske et al., 2018; Whitman et al., 2018). In theory, once developed meaningful soil quality indicators will inform policies, programs, standards or certifications by serving as proxies for stewardship that help drive human actions toward sustainable land use practices. For associated soil health assessment efforts to be legitimate, they must ensure that indicator-scoring and integration steps do not allow users to trade-off environmental or cultural services in favor of productivity (Baveye, 2017; Greiner et al., 2017).

MINIMUM DATA SETS

Accordingly, it might be useful to consider how indicators are added to, or removed from sanctioned soil quality indicator lists. Recent U.S. efforts to refine soil health metrics build on a "minimum data set" (MDS) of physical, chemical and biological properties using the same kind of consultative processes applied in the 1990s by NCERA-59 to gather expert opinion on candidate measures (**Figure 2**). Hopefully future work will articulate how advances in computing power and statistical methods will be used to generate unbiased evaluations of metrics, select indicators and quantify relationships between variables in lieu of subjective techniques. While some properties included in SHI's Tier 1, list can change over periods too short (e.g., pH) or too long (e.g., texture) to make them ideal stewardship indicators, they influence many functions as well as the rate and extent to which processes including soil change occur. Such properties might be viewed as covariates for biotic and soil-organic matter dependent indicators that reflect the cumulative effects of land stewardship.

According to the SHI Action Plan (SHI, 2016) (https://soilhealthinstitute.org/north-american-project-to-evaluate-soil-health-measurements/) to achieve Tier 1 status an indicator should be applicable across soil regions and groups using a standardized method and be adequately understood to classify soil health as poor, adequate, or good to fulfill production and environmental goals. Tier 2 indicators should show promise for the same objectives but may not be sufficiently developed to apply or interpret across all soils or management regimes. Finally, Tier 3 indicators are regarded by the SHI to be promising but in need of research describing relationships among measured values, soil processes, and effects of land management as well as methodological development. The Committee finds the reasoning behind the SHI's additions to the soil quality MDS unclear but appreciates their efforts have been mirrored by NRCS SHD activities that have produced a similar list of indicators (Stott, 2018). Both lists continue to include short term incubations and several enzyme assays that are intriguing but difficult to interpret universally and a few highly exploratory assays with high throughput potential. Many indicators are not firmly established enough to even meet Tier 2 criteria. This assertion is certainly supported by numerous presentations at the 2019 Soil Science Society of America's annual meeting in which most indicators were shown to be in development or discovery mode and nowhere near ready for blanket endorsement or use to assign good-to-poor ratings (Stewart et al., 2018; Jagadamma et al., 2019; Lorenz et al., 2019; Voger, 2019; Zuber and Kladivko, 2019). Even where indicators could meet Tier 1 criteria they may carry a different weight of information across regions systems or specific locations in terms of both importance and influence (Roper et al., 2017; Singh et al., 2019). The Committee questions NRCS's efforts to standardize an MDS of indicators via the Federal Registrar (USDA, 2018, FR 46703) (Stott, 2018) and hope this does not limit the development and use of other, more promising techniques that might be more regionally appropriate. Hopefully this is just a starting point with a list that is fluid in nature. We in no way want an approach that will limit new innovative methodologies. For example, whether one agrees wet aggregate stability is, or is not, a good soil quality indicator, most acknowledge it does not adequately describe the soil habitat or soil architecture experienced by microbes or roots and, is not useful to model water transport (Young et al., 2001). A pore-oriented approach that explores how soil biology interacts with surfaces to structure the soil and influences processes is likely to be more fruitful (Kravchenko and Guber, 2017; Rabot et al., 2018). Investment in newer methods (e.g., CT scanners) (Baveye et al., 2018) that quantify features regulating processes of interest might help us identify indicators that will be more predictive of soil services.

While a detailed critique of indicators selected by the SHI and NRCS (**Figure 2**) is not the focus of this article, and we appreciate the value of data and the methods currently available, the Committee cautions against "locking in" to proscribed methods because they have been widely used (e.g., short term C mineralization) despite notorious challenges associated with interpretation and, fears that insistence on standardization may actually work against method utility. The Tier 1 criterion of universal application of methods should be dropped as the primary filter for selecting soil quality indicators. Regionalization of standard chemical soil tests (e.g., soil phosphorus testing) has not, for example, posed a barrier to their use. Subjective aspects of test interpretation might be a bigger problem than methodological variability. Of course consistently applied methods are desirable for broad scale inventories that might backstop certifications or product claims but tailored measures are likely to perform better for diagnostic applications. The sensitivity and utility of many promising biological and physical soil health indicators are maximized by site- and farming system-based adaptations of sampling and analysis steps. As is true for medical tests that establish a context for testing by altering the diet or imposing stress, for example, indicator sampling regimes need to be targeted in space and time to minimize confounding factors to enable interpretation. It could likely be that the most valuable assessment of soil health is the improvement of associated ecosystem services from a baseline even on a single farm, much in the way that an individual's improvement of health is often better measured by tracking change over time using their own results rather than by comparing test results to a general reference value. The nature and mode of information delivery would need to differ for individual or group-level decision making.

From a public perspective, the decision to invest in the collection of certain data and not others might be questioned. The Soil Health Partnership, a FFAR-funded SHI partner that is a multi-entity private non-profit organization led by the National Corn Growers Association, is conducting on-farm research on cover crops and other soil health promoting practices and investing significant public monies into gather data. It will be interesting to see if their indicator choices, which include SHI's MDS and phospholipid fatty acids, the Cornell Comprehensive Assessment of Soil Health, and Haney Soil Health Test, which are costly compared to routine tests and, in some cases unproven, provide information of practical value to individual farmers. It is clear how, if designed effectively, this kind of coordinated sampling campaign could quickly compile valuable data that might lead to development of high impact soil health assessment tools. Both the rapid growth in the number of participants in the SHP demonstrating substantial farmer interest in soil health and buy-in from industry partners are unique and particularly promising aspect of FFAR supported efforts particularly when one considers that uptake and use of soil health information by stakeholders has previously been cited as a weakness (Bunemann et al., 2018). As we move away from a tradition of researcher-led

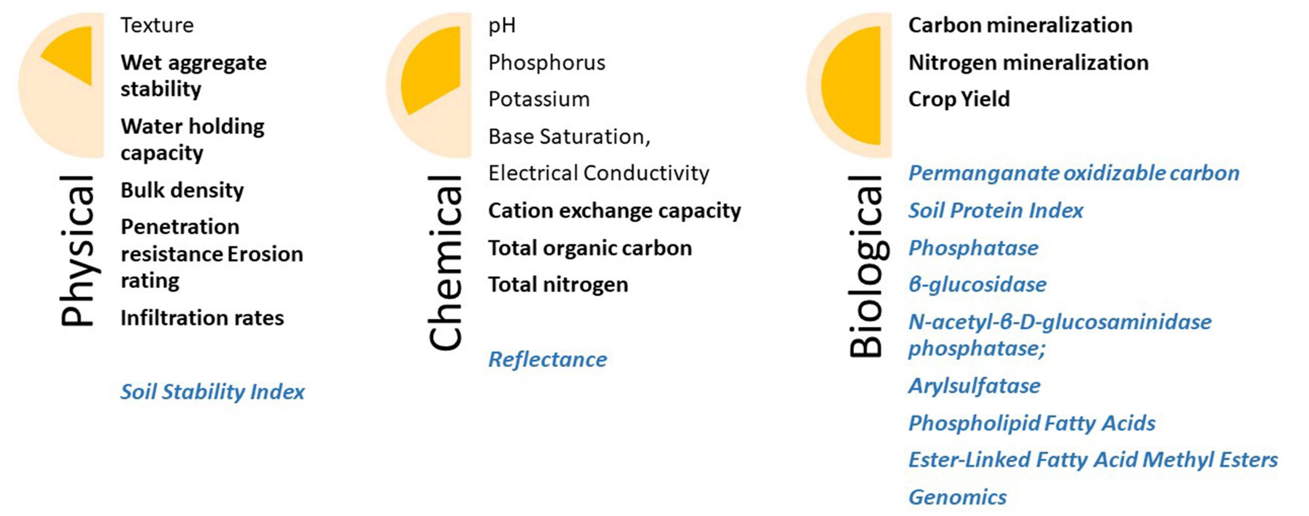

FIGURE 2 | Soil quality indicators recommended for inclusion in the U.S. minimum data set with variables that integrate change in years to decades (bold), that are considered Tier 1 (Black) and Tier 2 (Blue Italics) by the Soil Health Institute (https://soilhealthinstitute.org/north-american-project-to-evaluate-soil-health-measurements/) and NRCS SHD 2018 Federal Register Notice Docket No. NRCS-2018-0006 (NRCS, 2018), Notice of Recommended Standard Methods for use as Soil Health Indicator https://www.federalregister.gov/documents/2018/09/14/2018-19985/notice-of-recommended-standard-methods-for-use-as-soil-health-indicator-measurements. NCERA-59's 1994 MDS included: Physical (Texture, Bulk Density, Depth of Rooting, Infiltration, Water Holding Capacity, Soil Structure); Chemical (pH, N, P, K, EC, Soil Organic Matter); and Biological (Active C, Potentially Mineralizable N, Soil Respiration, Crop Yield) properties.

research on soil health that has pooled soil quality information obtained through participatory on-farm research (Sarrantonio et al., 1996; Wander and Drinkwater, 2000; Andrews et al., 2002; Wade et al., 2016; Ugarte et al., 2018) to gain an understanding of interactions between management practices, soils, and soil quality to a commercial R&D model what will it look like? It might be timely to ask questions about who pays for, and benefits from the information once it is compiled? Concerns that privately led efforts engaging famers-networks engaged in R&D might limit public access to the benefits of "microbiocapital" have already been raised in Europe (Granjou and Phillips, 2018). An evaluation of issues surrounding farm data ownership collected from an array of smart-sensor and other technologies related to precision agriculture provides something of a warning by suggesting one cannot make safe assumptions about the public availability of information (Ellixson and Griffin, 2016; Griffin, 2016; Wolfert et al., 2017).

MOVING FORWARD

SHP activities provide an exciting model for how the tradition of on-farm research, which has been widely used for soil health assessment, might evolve into an approach where user-groups marshal their data to improve management, direct planning or policy, and backstop product claims. However, it is critical that we map a path forward that is closely and continuously tied to rigorous, high quality, transparent science, and discourse. The SHI's Research Landscape Tool provides a research framework based on the premise that individual landholders will use indicators like soil tests for problem-solving as it relates problems to indicators, actions, functions and outcomes. From a researcher's perspective, it seems overly complex and difficult to align this vision with the supporting, provisioning, regulating, or cultural services listed by the Millennium Ecosystem Assessment[1] or related international efforts (FAO and ITPS, 2015) that use a natural capital framing to monetize ecosystem services (Costanza et al., 1997). From an applied perspective, however, one can appreciate that the market-based approach being applied aligns with planning and interpretation protocols used by multi-stakeholder groups. This framing also explains what the SHI means by research landscape factors, which in business terms include public awareness, government commitments, regulations, and influencing factors that include international economic and financial drivers (Coenen et al., 2012). Within this business framing, there are "niche" and "regime" level actors that compete for supremacy within the landscape to determine the rules and institutions that govern how industries resolve technical and environmental problems (Rock et al., 2009). Within the current soil health landscape framing, academics and scientific organizations have unfortunately become niche actors in that they do not set the terms or structure the process for soil health assessment by the private sector. Fortunately, the academic community has been invited to actively participate in the soil health discourse by SHI. It is critical that we take them up on this and engage. How well interpretive frameworks for soil health ultimately protect the soil resource will depend on how, and for whom, they are applied. Other entities developing green labels or business standards incorporating soil quality metrics sometimes do, but often do not, include or invite the research community to represent the public's interests and instead assume non-profit entities will play that role. Involvement of producers and researchers in research enterprises is known to lead to more successful adoption of technology by end-users when all participants play an active role in decision making (Swanson et al., 1998). The research community working at public institutions will have to work to maintain a clear voice to help stakeholders clearly define and defend public interests as it works to increase soil's productivity.

NCERA-59 members admit we are concerned by the perceived transference of soil health leadership to the private sector away from public institutions including NRCS, which administers our Nation's conservation programs, maintains the Soil Survey, and facilitates the use of information through the National Soil Survey Information System (NASIS) and Soil Survey Geographic System (SSURGO) (Levin et al., 2017). By officially sanctioning specific soil health indicators, the NRCS SHD may help to reinforce technological and institutional role played by government that allow them to retain influence over the soil health landscape in the U.S. (Geels and Kemp, 2006). We doubt the Soil Health Institute, which aspires to become "the primary resource for soil health information and research" (SHI; "https://soilhealthinstitute.org/goals/), or any public entity, will be able to: (i) sustain multi-entity efforts to build and maintain the research infrastructure and capacity needed to develop, store and share large volumes of data, (ii) have the trust and authority required to set clear standards for data collection and sharing, and (iii) have the ability to foster the development of effective predictive models, indicator scoring frameworks or decision support tools needed by the public (see Ecological Systems Committee (ESC), 2016 for overview of U.S. soil health needs) without strong ties to public institutions. If public-private entities are to become the public's primary soil health resource, then a clearly articulated public comment and interface plan is needed for any enterprises receiving significant public monies, and data standards including rules on metadata and data access must be put in place along with a detailed open data architecture.

To move forward, NCERA-59 members encourage the research community to move beyond arguments about methods standardization while noting the need to adapt an MDS of indicators and to tailor techniques for different soil types. Instead, we join the call to focus efforts on developing interpretive frameworks that support meaningful application to specific sectors (Stewart et al., 2018). A smart "minimum data set" will be derived without selective/arbitrary reasoning for, or against, indicator selections, threshold establishment, and direction toward action. We should learn from, instead of repeat, the past to allow us to rapidly develop ways to assess soil health which, along with soil change and soil security, is a derivative of soil quality. Agronomic applications must provide clear scientifically based reasoning needed to promote soil stewardship predicated on site specific evaluations of multiple soil functions. Broadening of our public universities' ability to partner with industry to meet short- and long-term goals for soil health can help growers and public interest groups set normative goals needed for soil stewardship. Public-sector soil science research capacity must be maintained to develop the soil quality indicators and frameworks needed to underpin soil health assessment.

DATA AVAILABILITY

All datasets analyzed for this study are included in the manuscript and the supplementary files.

AUTHOR CONTRIBUTIONS

MW, LC, MC, JMG, JLMG, WH, SJ, DO, LT, MR, and RT contributed to concept development during at least one of two NCERA-59 meetings held in 2016 and 2017, MW developed the primary text and LC, MC, RD, JMG, JLMG, WH, SJ, DO, LT, MR, SS, RW, and RT provided additions and edits.

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