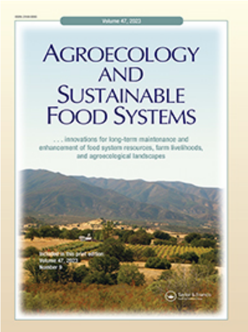

Agroecology and Sustainable Food Systems

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjsa21

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To cite this article: Prabhjot Singh, Nicholas C. Kawa & Christine D. Sprunger (31 Oct 2023): “More questions than answers”: Ohio farmers’ perceptions of novel soil health data and their utility for on-farm management, Agroecology and Sustainable Food Systems, DOI: 10.1080/21683565.2023.2270928

To link to this article: https://doi.org/10.1080/21683565.2023.2270928

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
https://doi.org/10.1080/21683565.2023.2270928

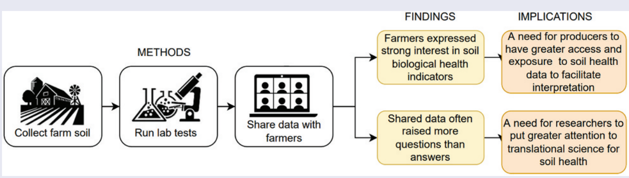
"More questions than answers": Ohio farmers' perceptions of novel soil health data and their utility for on-farm management

Prabhjot Singh[a,b], Nicholas C. Kawa[b,c], and Christine D. Sprunger[a,d,e]

[a]School of Environment and Natural Resources, The Ohio State University, Columbus, USA; [b]Environmental Science Graduate Program, The Ohio State University, Columbus, USA; [c]Department of Anthropology, The Ohio State University, Columbus, USA; [d]W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, USA; [e]Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, USA

ABSTRACT

Soil health has become an emergent focus of contemporary agricultural research, yet little work has addressed how soil health data – and biological indicators in particular – are interpreted by farmers and potentially incorporated into their decision-making. To address this gap, in-depth interviews were conducted with 20 Ohio farmers after sharing a soil health report that detailed physical, chemical, and biological indicators from at least two sampled fields from their farms. Research findings demonstrate that while farmers expressed strong interest in soil biological health indicators specifically, the data often raised more questions than answers for participants. Specifically, three main themes emerged in the interviews: 1) uncertainties in interpreting the soil health indicators, 2) questions regarding translation of soil health data into management, and 3) affirmation of existing management choices. The first two response themes point to a need for scientists to develop greater access and exposure to soil health data to facilitate interpretation. Furthermore, researchers and extension agents can play a critical role in guiding recommendations for potential application of soil health data in on-farm management. While research on soil health has widely expanded in recent years, this study highlights the need for greater attention to its translational science and the co-production of knowledge.



KEYWORDS
Soil health; soil biology; agroecology; farmer interests; farmer decision-making

CONTACT Christine D. Sprunger sprunge5@msu.edu W.K. Kellogg Biological Station, Michigan State University, 3700 E Gull Lake Dr. Hickory Corners, Columbus, MI, USA

Supplemental data for this article can be accessed online at https://doi.org/10.1080/21683565.2023.2270928

Introduction

Today, there is a growing emphasis on soil health in the agricultural community because of its important bearing on both crop productivity and ecosystem services (Culman et al. 2013; Sprunger et al. 2021). This expanding interest in soil health has led to active dialogue among scientific researchers, extension educators, and farmers on how soil health should be defined and quantified (Stewart et al. 2018; Wade et al. 2021; Wirth-Murray and Basche 2020). However, little research has sought to address how soil health data, and biological indicators in particular, can be effectively translated into on-farm management and contribute to farmer decision-making (Mann et al. 2021; Wood and Blankinship 2022). Part of the reason behind this gap is that it requires an interdisciplinary approach that draws on both soil science and social science methodologies. It also requires researchers and producers alike to grapple with real-world constraints and uncertainties that complicate the application of such data for improving management outcomes.

At a rudimentary level, soil health is the continued ability of soil to function as a living ecosystem that sustains plants, animals, and humans. It incorporates measures of soil quality (i.e. nutrients or soil fertility) and soil tilth (i.e. soil physical characteristics), along with soil biology. For this reason, soil health should be understood as a holistic framework that considers chemical, physical, *and* biological processes of an ecosystem and adopts measures that reflect each of these. While the terms soil quality and soil health were once treated nearly synonymously, these distinctions in the two concepts began to take hold in the 1990s (Lehmann et al. 2020). To be sure, some chemical and physical soil health data have been available to farmers for decades through commercial soil testing, but biological data are only recently becoming more accessible (Lehmann et al. 2020; O'Neill, Sprunger, and Robertson 2021). Soil biological health indicators are a critical aspect of soil health because they encompass parameters that directly measure organisms and indicators that reflect biological activity (Pankhurst 1997). Moreover, soil biological health indicators are often more sensitive relative to other measures for detecting recent changes in management (Culman et al. 2013), which is critical as farmers continue to adopt soil health promoting practices. However, most farmers lack regular access to soil biological indicators and active debate remains in the scientific community as to which soil biological health indicators are most useful or most representative of soil health (Fierer, Wood, and Bueno de Mesquita 2021; Martin et al. 2022; Wade et al. 2022).

Moreover, a major lack of standardization for soil biological health indicators, has made drawing conclusions and informing management challenging (Wade et al. 2018). For instance, Fierer, Wood, and Bueno de Mesquita (2021) make the case for using soil microbes as a source of information on soil biological health, and pose, if and when, these microbes are indicative of different nutrient cycles that can be informative of soil health. For example, broad microorganism counts and classification may be unhelpful to a farmer more interested in ecological function, including key nutrient cycles such as nitrogen. However, assessing a specific genera of microbe could have the potential to be a useful metric for management guidance and soil health improvement strategies because of their connection to key global nutrient cycles. However, interpreting and translating metagenomic sequencing and even general microbiome sequencing data and relating it to soil functions, such as nitrogen cycling, is challenging and underdeveloped (Graham et al. 2016). In contrast, soil organisms such as nematodes can be useful measures of soil health as these biota fill niches at several trophic levels in the soil system (Martin and Sprunger 2022; Neher 2001). Due to their abundance and position in the soil food web, nematode community composition is correlated to multiple soil functions including nutrient cycling and decomposition making them useful bioindicators of soil health (Lu et al. 2020; Neher 2001). Similarly, measuring different enzymes produced by microbes that are associated with specific elemental cycling can be a good indication of organic matter decomposition and nutrient cycling in the soil system (Alkorta et al. 2003; Ferraz-Almeida, Naves, and Mota 2015). While enzymes have been studied in soils for over 100 years (Nannipieri, Trasar-Cepeda, and Dick 2018), they have infrequently been offered to farmers as sources of information. Similarly, soil microbes have been explored through academic research for many years, but microbial ecology has rarely been translated into soil management guidance to farmers (Fierer, Wood, and Bueno de Mesquita 2021). We are beginning to see how nematode counts can link back to farm outcomes (Martin et al. 2022), however there is still a need for research to determine how soil biological health indicators fluctuate on-farm, how they are tied to farm management, and report these findings to farmers. Ultimately, many soil biological health indicators have been designed for research purposes and are currently difficult to interpret as actionable outcomes for farmers. To better assess the utility of soil biological health indicators, farmer input is likely needed.

A primary goal of soil health is to provide farmers with a more holistic set of indicators that can aid in management decisions. However, before soil health indicators can assist with management, soil health tests must align with farmer perceptions of soil health within their own farm operations. For example, one study looking into farmer perceptions of soil health found that farmer-deemed “best” and “worst” fields aligned with multiple soil health parameters, especially soil biological health indicators (O’Neill, Sprunger, and Robertson 2021). This finding was similar to that of Rekik et al. (2020) and Liebig and Doran (1999) who demonstrated that farmers are frequently assessing their soil quality and are often able to determine soil fertility based on experience and observation. Similarly, Karltun, Lemenih, and Tolera (2013) found that farmer perceptions of soil health consistently aligned with soil organic matter content. However, while farmers are adept at gauging general soil health, they are still interested in receiving more technical and quantitative soil biological health data (Sprunger 2015). Wade et al. (2021) demonstrated that other actors in the agricultural sector have actually underestimated farmers' interest in soil biological health indicators. Mann et al. (2021) also highlighted that farmers found comprehensive soil health testing (CSHA – which emphasizes biological soil health indicators) as useful and wanted tests to be commercially available. These authors have also made the case for establishing more dynamic and active mechanisms for sharing soil health information with farmers and making testing more accessible.

However, making data available to farmers is not enough – soil biological health indicators also need to be easily interpretable and useful for on-farm decision-making. For example, while the majority of farmers in Mann et al. (2021) intended to change their management after receiving soil biological health data, there were still some farmers who were unsure of the data or did not find it useful. Furthermore, the majority of these farmers stated they did not yet understand the data, and thus would be unable to use it. Beyond data sharing, farmers emphasized the need to link soil health indicator values to practical application for management. Simply measuring soil health indicators does not lead to soil health outcomes and overall enhanced sustainability (Doran and Zeiss 2000; Wade et al. 2022). For this reason, research developing a foundation for consultation between researchers and farmers is necessary to help identify changes needed to understand and enhance soil health.

To address this gap, this study investigates how farmers interpret soil biological health indicators and seeks to identify the potential value of such indicators for informing farmer management practices. Understanding how farmers grasp soil biological health indicators is key to helping farmers adopt soil health promoting practices (Lobry de Bruyn 2001). Farmer feedback can also play an important role in guiding the development of soil biological health metrics and how these may be distributed and implemented in extension activities (O'Neill, Sprunger, and Robertson 2021).

Drawing on in-depth interviews with 20 farmers in Ohio, the primary objectives of this research were to:

(1) Identify which soil health indicators are perceived as most useful.
(2) Assess farmer knowledge gaps related to various soil health indicators.
(3) Understand the challenges in translating soil biological health data into on-farm management.
(4) Examine how soil biological health data inform farmer management decisions.

Methods

Farmer recruitment and participation

Farmer participation was critical to this research. Prior to data collection, surveys and interview guides were approved by The Ohio State university's Institutional Review Board. Participant recruitment was based on volunteer sampling and began during the Conservation Tillage and Technology Conference (CTTC) in March of 2020, which hosted several hundred row-crop farmers from across the upper Midwest. Further recruitment was facilitated by OSU Extension Educators across Ohio. Due to time constraints and financial limitations, volunteer-based sampling was the most feasible for this project. Participating farmers were incentivized to participate through the cost-free soil health reports and consultation along with a $75 Visa gift card to compensate them for their time.

Data collection

Each participant farmer was sent instructions for mail-in soil sampling and asked to complete management surveys for two fields of their choice. Farmers were encouraged to choose a best field and a challenging field so that the results of the soil health tests could be compared and discussed with the researchers. Surveys were used to gather field management history from the sampled field, including soil amendments, fertilizer application, tillage, and crop over a four-year period (2016–2019). Of the 20 participating farmers, all farmers submitted two soil samples and two corresponding surveys, except for two participants, who submitted 4 samples and 4 surveys. Thus, there were 20 total farmers interviewed and 44 total soil samples and surveys.

Once soil samples were received, a suite of soil health analyses were conducted by Spectrum Analytics (a commercial lab for soil testing) and the academic lab (Table 1). The soil health test results were organized in a report that provided a basic guide for interpreting soil health measures, including the values for each measured parameter of the fields sampled. Farmers were mailed soil health test reports along with a soil health factsheet that helped to further explain the results. The factsheet described each of the soil health tests performed on farmer samples including some background information on the measured parameters, diagrams and graphics to improve understanding, and in some cases optimal value ranges for the indicators. Soil health reports also included sections of this information that were likely less familiar to farmers to serve as a reminder as they read their results.

Next, twenty semi-structured interviews were conducted during the winter and spring of 2020. Interviews were conducted in part to share the soil test results with farmers, introduce them to the indicators which are not traditionally offered by commercial testing labs, discuss farmer

Table 1. List of soil health indicators conducted in this study and their functional significance.

Soil Health Indicator	Functional Significance
Soil Chemistry	
Nutrient analysis	Nutrient levels and availability, pH
Soil Organic Matter via Loss On Ignition	Fraction of soil that consists of plant or animal tissue in various stages of decomposition and influences soil biological, chemical, and physical processes.
Permanganate oxidizable C (POXC)	Active pool of soil C, associated with microbial biomass
Soil Biology	
Respiration	Respired CO_2, measure of microbial activity
Soil protein	Available pool of organic soil N
Enzyme activity	Insight into microbial C, N P, S limitations and demand
Beneficial nematodes	Indicators of soil food web structure and function
Soil Physics	
Texture	Influences C storage, water and gas exchange
Aggregate stability	Wet sieving to reflect physical structure and soil tilth

rationale behind field selection, and lastly, assess potential utility of those data for future decision-making. While a sample of 20 farmers is not representative of the broader agricultural community in Ohio, it does provide valuable insights into how producers qualitatively assess the value of soil health measures and their utility for on-farm management. As Hennink and Kaiser (2022) have demonstrated, many qualitative studies using empirical data reach saturation – the point at which "gathering new data about a theoretical construct reveals no new properties – within a narrow range of interviews (9–17), particularly when working with relatively homogenous study populations (e.g. full-time Ohio farmers) and narrowly-defined objectives (e.g. identifying farmers' perceptions of soil health data).

Interviews took place virtually via Zoom due to the COVID-19 Pandemic and involved the farmer, a soil scientist, an anthropologist, and a graduate student researcher. All interviews followed a semi-structured interview guide (Supplementary Material). With the permission of participants, interviews were recorded and stored in a password protected folder in OneDrive, which was accessible by researchers only.

Data analysis

Interviews were over Zoom video conferencing software and were digitally recorded in their entirety after receiving informed verbal consent from study participants. A transcription of the audio recording was generated by Zoom, and then checked against the full recording for accuracy by a member of the study team. A member of the study team removed all identifiers from interview transcripts, and de-identified transcripts were then uploaded into Dedoose qualitative analysis software program.

Coding of the interviews began with deductive codes (e.g. soil organic matter, enzymes, nematodes) that were drawn from the interview protocol. Then, the first and second authors developed inductive codes by reviewing an initial set of transcripts, and meeting to discuss any additional topics that emerged from the interview data. These topics were added to the existing deductive codes, and an expanded set of codes was tested on additional interviews, with any additional emergent codes added until saturation was reached. To assess the perceived utility of the soil health indicators, our analysis here focuses specifically on coded data related to soil health indicators and their usefulness to farmers ("Are some of these soil health indicators more useful than others? If so, why? And how might you utilize these data?").

Results

Farm demographics and characteristics

Each participant farmer submitted a management survey for two selected fields, apart from two farmers that selected an extra two fields each (Table 2, $n = 44$). The overwhelming majority of our participant farmers were men, with only 5% identifying as female. Farm acreage varied across fields, ranging between 20 and 566 ha. Seventy-Three percent of the fields reported on in this study were owned by farmers, while 27% were rented. Forty-five percent of the fields sampled in this study were under no-till management. The management survey also included information on the fields' crop rotation, organic certification, amendments and organic inputs, livestock grazing, and tile drainage.

Table 2. Characteristics of participating farmers and evaluated fields.

Characteristic	Percent of total sample
Gender (n = farmer)	Total Sample (n = 20)
Male	95%
Female	5%
Land Ownership (n = field)	Total Sample (n = 44)
Owned	73%
Rented	27%
Certified Organic	Total Sample (n = 44)
Yes	9%
No	91%
Livestock/Grazing (n = field)	Total Sample (n = 44)
Yes	25%
No	75%
Tile Drainage (n = field)	Total Sample (n = 44)
Yes, pattern	41%
Yes, random	18%
No	41%
No Tillage (n = field)	Total Sample (n = 44)
Yes	45%
No	55%

Perceptions of soil health indicators

When asked about the utility of the soil health data provided, the 20 farmers interviewed for the study fell into three general categories: those who identified specific soil health indicators ($n = 12$), those who described all the data as useful ($n = 4$), and those who did not mention any specific indicators ($n = 4$) (Figure 1). Of the 12 farmers who described specific indicators as useful, six discussed enzyme activity, four mentioned organic matter values (e.g., soil protein, Permanganate Oxidizable Carbon (POXC), and respiration), and three identified the nematode indices (including one farmer that also mentioned enzymes). Notably, all of these are novel soil biological indicators not yet offered in commercial labs.

Among the interviewees, three prominent themes also emerged during interviews that crosscut the groups identified above. These themes were: 1) uncertainties in understanding the soil health indicators themselves, 2) translation of the data into soil management practice, and 3) affirmation of existing soil management practices. These qualitative findings are discussed in detail below.

Uncertainties in understanding soil health indicators

Due to the sheer novelty of much of the data that was shared with farmers through the soil health reports, many individuals expressed uncertainties about

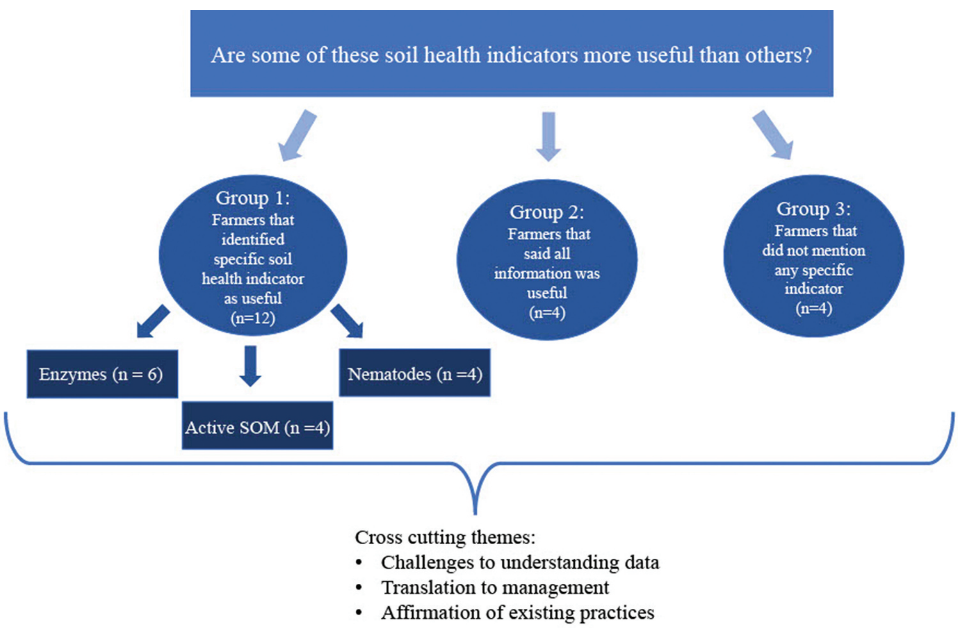


Figure 1. Visualization and groupings of farmer responses to questions related to soil health indicators and their utility. Active SOM = active soil organic matter indicators (soil respiration, active carbon, and soil protein).

interpreting the various measures provided, including soil biological health indicators (POXC, Respiration, and Soil Protein), nematode indices, and enzyme activity (Table 1). For example, several farmers identified the enzyme activity data as being useful to them (6 of the 20), but they varied considerably in how they interpreted the significance of these data as well as the questions that remained for them (see Table 3). As one farmer exclaimed during the interview:

> . . .this enzyme activity report, man, that just looks like there's more questions than answers. . . Seems like it! (Farmer 172)

Though some farmers expressed uncertainties regarding the interpretation of certain indicators, others raised questions regarding relationships among different data. For example, another farmer inquired:

> The enzyme activity report. I mean I don't understand the numbers but. . . Is there a correlation of a lower phosphorus level to a lower phosphorus cycling and similar for carbon cycling? (Farmer 214)

While this farmer expressed clear interest in the enzyme activity report, he shared doubts about his grasp of the data and sought instead to ask whether such measures corresponded with soil chemical properties from nutrient test reports that were more familiar to him.

In addition to questions about enzyme activity, other valuable queries were

Table 3. Representative quotes from Ohio farmers in response to the question "are some of these soil health indicators more useful than others? If so, why? And how might you use these data?"

Indicator	Representative Farmer Responses
Enzymes	"I guess it [enzymes] tells me that we probably don't need as much phosphorus and nitrogen, that it's naturally being released or cycling in the soil. So, we should be able to cut back with our fertility program over the years" "This enzyme active report, man, that just looks like there's more questions than answers, I think. Seems like it!" "Yeah, the enzyme activity report. I mean I don't understand the numbers but . . . "
Nematodes	"Yeah the nematodes . . . we've heard about this, but I've never seen it in black and white before, so this is nice because this is how that works." "I guess just being exposed to the nematode indices and the enzyme activity report. Uh, having this as a as a baseline, so to speak with plans to make changes it"
Active Organic Matter	"Active carbon availability I think is something very interesting . . . I'm all about understanding how we can better utilize carbon, carbon sources to increase production and improve overall soil health" "Well, I kinda liked your explanation of the carbon and the respiratory explanation. That's something I wasn't really familiar with . . . after you explained the test, it even got more interesting"

shared regarding the interpretation of the nematode indices. For example, one individual asked how the nematodes assessed for the soil health indices compared to the familiar and quite damaging soybean cyst nematodes, asking:

> Uh, we don't want cyst nematodes, but apparently we do want these other nematodes? (Farmer 204)

To clarify this point of confusion, the research team discussed the diversity of niches that nematodes fill in the soil food web as well as how beneficial nematodes were counted to calculate the nematode indicators for the study.

Farmer responses did not necessarily indicate skepticism regarding the science, nor did they vocalize any negative feedback regarding the soil health values. This may have been due to the courtesy bias where farmers would be hesitant to share any criticisms with researchers directly.

As noted earlier, four farmers in the study did not mention any specific soil health measures as being useful to them, but this group contributed other valuable observations and queries about the soil health data. For example, one farmer in this group underscored how developing a basic familiarity and understanding of the data was essential to determining utility, stating:

> The [data] that we talked about and that I understand are obviously much more useful to me. (Farmer 173)

Furthermore, among the four farmers who described "all the data as useful," two went on to discuss challenges they had in absorbing such novel information in a comprehensive fashion. This is illustrated in the interview excerpts below:

> They were all interesting to me, so I don't know. I need to sit down and actually I haven't had much time to look at it closely today. . .just to get the full understanding of what I'm looking at. (Farmer 286)

> All the information is good. Yes, it's all good information. I guess how it all links together and. . .what do we need to do to improve things, yeah, I guess that would be the next step to go. (Farmer 129)

Clearly, there remain gaps in how soil health data are communicated from soil scientists to farmers in ways that are accessible and intelligible. This challenge is due in large part to the novelty of these data for many farmers and the simple need for repeated exposure to such measures to develop greater familiarity. However, improving basic comprehension does not necessarily eliminate uncertainties in the interpretation of soil health data. As the last farmer quoted above, remarked to the research team: "[It] answers some questions and then it raises more questions" (Farmer 129). This observation is especially important because as farmers gain access to these novel soil health indicators, they may find themselves asking more questions about how soil biological health is shaped by management decisions and vice versa.

Translation to management

A second prominent theme from the interviews concerned the translation of soil health data into on-farm management and actionable change. When farmers asked about translation to management, the question was often phrased as "how can we change that [soil health indicator value via management]?" For example, one farmer commented on the general utility of the organic matter indicators but then asked about translation to management:

> The soil active organic matter indicators. We're always talking about changing organic matter. And how do we change organic matter? (Farmer 145)

Similarly, a farmer stated his interest in changing management to improve the soil health values.

> . . . the active carbon availability I think is something very interesting . . . I'm all about understanding how we can better utilize carbon sources to increase production and improve overall soil health so the carbon piece is really fascinating to me with this and what we can do to change that. (Farmer 89)

A third farmer was interested not only in how to improve his soil health values, but also how those improvements would require addition calculations of "return on investment" or "ROI." He asked,

> Well, how do we make it better? How can we take some of these values and then can we implement a practice or an application or management strategy to improve those . . . I guess that's the main thing I would like with the information. . . and then we also [have to] look at ROI too. I mean, it might cost me $50 to put manure on, but I only get $10 worth of value. (Farmer 123)

This suggests that while novel soil health data may be useful to farmers, simply sharing the values with farmers is not enough. For such data to be incorporated into farmers' decision-making, the practical implications of the indicators as well as the costs of implementing new management practices must be identified.

Among all the interviewees, only two farmers acknowledged how the soil health data presented by the research team could directly inform management changes to their fields. After one of these farmers learned that the active nutrient cycling on his fields was higher than he anticipated, he remarked:

> I guess it tells me that we probably don't need as much phosphorus and nitrogen, that it's naturally being released or cycling in the soil. So, we should be able to cut back with our fertility program over the years . . . Cut back on more of the synthetic fertilizers or even chemicals. (Farmer 21)

This simply illustrates that such novel data can prompt individual farmers to entertain changes to management, including synthetic amendment reduction. Although the majority of farmers did not discuss how specific indices would inform their future management, a few did mention that having such baseline data would be useful for future assessments of soil health. The farmer who identified both enzymes and nematodes as useful indicators made this basic point, stating:

> I guess just … being exposed to the nematode indices and the enzyme activity report. Having this as a baseline, so to speak with, with plans to make changes… It'll be really interesting to see … with an additional level of management… what impact that might make overtime. (Farmer 180)

Affirmation of existing practices

The third recurring theme among farmer interview responses was how the soil health data affirmed practices that farmers had already implemented. There were a total of four farmers who mentioned that the soil health report values validated their existing management. For example, one individual commented:

> Well, I suppose I may keep doing what I'm doing. Don't go out there and plow up the field and change it all over and try something different. I mean, it looks like maybe we're going the right direction. (Farmer 230)

Another farmer spoke specifically about how expected ranges for the organic matter indices offered in the soil health report were a useful validation tool for farmers:

> Ranges for the organic matter … knowing some of those numbers … we can see some of those physical things that maybe give them [farmers] reassurance that you know, yeah, what you're doing is working. (Farmer 223)

This farmer further expressed that as a salesman in the industry he shared with clients that building organic matter in the soil was often a better solution to many problems when compared to the application of chemical amendments.

Many farmers in this study engaged in soil conservation practices, including no-till and cover cropping. Two farmers that had adopted these practices argued that all of the soil health data were useful to them, and they specifically discussed how the data affirmed their adoption of no-till, as highlighted in the quotes below:

> I mean, I guess all of it was pretty helpful … So that's why I like these kind of things. You always learn something…This is why I'm no-tilling you know. So, any kind of documents that you have that can show you more why you're doing it—this is helpful. (Farmer 80)

> Yeah, I thought that was pretty cool too. I guess…just to be able to see…kind of proof I have [that] no-till is doing its job. (Farmer 199)

In these aforementioned cases, the soil health data provided by the research team did not lead to active questioning of ways to improve their management, but rather was perceived as useful for simply affirming their conservation management decisions.

Discussion

Soil biological health indicators resonated with farmers

The objectives of this study were to identify which soil health indicators were perceived as most useful to farmers and what gaps still existed to farmers regarding the soil health indicators. Thus, this study worked to assess farmer perceptions of various soil health indicators that were quantified on their respective fields. Researchers also aimed to better understand the challenges of translating soil biological health data to applied on-farm management. Additionally, researchers aimed to determine if these soil biological health indicators were informing farmer management decisions. When farmers were asked to identify soil health indicators that appeared to be most useful to them, a majority mentioned a specific soil biological health indicator. This is especially noteworthy given that current soil testing available through commercial laboratories do not offer such tests (O'Neill, Sprunger, and Robertson 2021). Interviews revealed that thirty-percent of farmers specifically mentioned enzymes, which is surprising, given the complexity around understanding enzymes through a soil health lens (Fierer, Wood, and Bueno de Mesquita 2021). However, individual responses do also illustrate some of the complexity surrounding enzymes. For example, while some farmers mentioned understanding the link between enzymes and nutrient cycling, others had questions regarding the significance of individual values or "what the numbers meant." In addition to enzymes, farmers also indicated interest in nematodes and active organic matter (i.e. soil protein, permanganate oxidizable carbon, and soil respiration). Several farmers also suggested that these indicators intuitively aligned with their perceptions of a healthy soil. These observations align with a study by O'Neill, Sprunger, and Robertson (2021) in which Michigan farmers had been asked to identify their "best" and "worst" fields and those that were deemed to be best by producers show significant differences in their biological parameters but not in inorganic chemical tests. Other farmers seemed to appreciate active organic matter indicators specifically because of their apparent novelty and simplicity. This is critical as farmers seem to really connect with indicators that they are able to grasp and understand, even if the concept is new (Toffolini, Jeuffroy, and Prost 2015). Our results are a departure from the Mann et al. (2021) study that reported that farmers seemed to gravitate more toward soil physical health characteristics. However, this difference could partially be explained by the fact that our soil biological health indicators were vastly different from the ones reported by Mann et al. (2021).

Given that farmers were exposed to numerous soil health indicators, we were equally interested in identifying when farmers had questions or challenges in understanding the soil health test reports. Perhaps one of the biggest challenges for farmers in our study was comprehending the diverse array of novel data that were shared in the comprehensive soil health reports. This is an admitted flaw within soil health research and demonstrates the need to narrow soil health indicators to those that are most useful to farmers (Wade et al. 2022). For example, most farmers do not have regular access to soil health indicators such as enzymes and nematodes. In fact, many of the farmers associated nematodes with soybean cyst [*Heterodera glycines]* nematodes rather than beneficial free-living nematode populations. This is a common conflation also made within the scientific community because soybean cyst nematodes are known to be the single most damaging pathogen in United States agriculture (Tylka and Marett 2014). Free-living nematodes, on the other hand, are the earth's most abundant metazoa and are critical for nutrient functioning and ecosystem health (Ferris, Bongers, and de Goede 2001; Neher 2001). Moreover, recent studies have demonstrated the important link between free-living nematodes and soil health (Martin and Sprunger 2022; Martin et al. 2022). Thus, exposing farmers to beneficial nematodes will be important as scientists look to further quantify soil biological health within agroecosystems. As mentioned above, enzyme activities also prompted quite a few questions surrounding interpretability and usage. Taken together, it's clear that while soil biological health indicators may have resonated most with farmers, but they also left farmers with the greatest number of questions.

Translation of novel soil health data into farmer management

During the various interviews, farmers asked about ways to improve the soil biological health indicator values. These individuals were looking for tangible ways to change their management and sought advice on how to do so from the research team. These questions often demonstrated that farmers were trying to understand the linkages amongst soil health, fertility, and yield. For instance, several farmers mentioned that they were actively working to improve organic matter values because they saw it as critical for maintaining crop productivity and overall soil health. These findings align with observations by Kelly, Allan, and Wilson (2009) who noted that farmers typically find soil health indicators most useful when direct application of the data are clearly established. However, offering recommendations for farmers can be challenging for researchers as there are few studies that measure these novel biological indicators on active farms with year-to-year changes (Mann et al. 2021; Williams, Colombi, and Keller 2020). Additionally, the multifaceted nature of soil ecosystems (i.e., variation in parent material, topography, climate, and vegetation) coupled with the unique history of each field adds a layer of complexity to understanding the values of these soil health data. Prior research has highlighted the importance of offering flexible advice that can fit with contextual realities of farmers individually (Brown, Nuberg, and Llewellyn 2020). Hence, researchers have identified the need to provide further consultation on the soil health indicators with the goal of translating the data for practical use on-farm. In other words, soil health data must be incorporated into individualized soil fertility and nutrient management recommendations (Franzluebbers et al. 2022).

Additionally, the extent to which farmers are willing to use soil health data for change depends on the source of the information, individual management goals, and even a farmer's particular learning pattern (Kilpatrick and Johns 2003). For example, one farmer inquired about "return on investment" and the associated cost of working to build soil organic matter. This aligns with questions posited by Wood and Blankinship (2022) surrounding the economic cost of increasing organic matter and the extent to which increases in soil C are economically optimal. Even if farmers have a specific soil health indicator in mind that they would like to improve over time, there is still the looming question: "is it worth it?" In contrast, there were four farmers in our study that declined to specify any indicator as useful. Rather farmers asked questions or even stated that they needed more time to digest the information. Additionally, two of the farmers who said that all data were useful mentioned needing more time to know how soil health test reports might be useful. As farmers develop a greater familiarity with soil health data, there may be a clearer sense of how farmers might begin to use such data to inform management (Turner et al. 2019). Our study highlights that soil health data may be more useful for farmers when it is paired with consultation and collaborative discussion with either extension educators or research scientists. Such consultations can also provide opportunities for research scientists to identify the utility of individual soil health indicators as well as gaps in translation of such measures into practice. As Gutknecht et al. (2022) note, co-production of soil health knowledge with farmers is a critical step in advancing soil health. Participatory soil health research done in collaboration with organizations like the Soil Health Institute and the Soil Health Partnership, for example, can also lead to the development of more impactful and relevant management recommendations for producers too.

Another noteworthy theme was that the soil health data affirmed existing management practices for a subset of the participant farmers. Multiple farmers mentioned that the soil health data demonstrated that they were on the right track and that they would continue to incorporate management practices such as no-till and nutrient amendments. Soil respiration, soil protein, and POXC were indicators that most commonly affirmed farmer management practices. Interpretation, translation, and data presentation likely influenced farmer interest in these values. For example, soil respiration, soil protein, and POXC farmer values were presented in a way that demonstrated where individual farmer values were situated in comparison to thousands of other on-farm data points. For instance, based on data collected from 2,000 + on-farm data points across the upper Midwest using data published from Sprunger et al. (2021) and Culman et al. (2022), farmers could see if their soil health values were in the top 25th percentile, median, or 75th percentile relative to soils with a similar texture. Situating soil health values by texture is a useful exercise and helps farmers assess optimal soil health ranges that are realistic to reach for on their specific fields. For example, in the soil health test reports, we were able to state, "your POXC value is ____ % greater than most farms with your same soil type in the upper Midwest." Since soil health indicators are relatively new, it can be hard for farmers and researchers to know what a "good soil health test" value is for a given soil type. This highlights the importance of a growing number of large soil health assessments across the United States (Culman et al. 2022; Liptzin et al. 2022; Sprunger et al. 2021; Zuber et al. 2020). Continuous efforts to conduct soil health assessments across a wide range soil types and managements will be critical as scientists and extension educators further work to communicate soil health findings with farmers.

Conclusions and implications

The findings of this study demonstrate that while farmers express interest in soil biological health indicators, the data often raised more questions than answers for the producers in this study. For soil biological health data to be interpreted and utilized more effectively by producers, they likely need 1) greater exposure to these indicators (e.g. multiple seasons of data collected) to be able to discern what "good" and "bad" numbers look like for them and their individual fields, and 2) guided recommendations from researchers or extension agents with expertise in biological indicators, who can aid in the translation of these data into on-farm management. One way to address these remaining challenges is to encourage continued farmer participatory action research, sharing of novel soil health data with farmers, and providing consultation to farmers that is specifically tailored to their fields. Participatory action research is an approach to research that involves the collaboration of researchers and those impacted by the study (in this case farmers) to address the problem or question at hand (Carberry, 2001). A noteworthy finding, however, is that soil health data did confirm existing management practices for a subset of farmers, demonstrating the value of these novel soil health indicators. Future research is needed to understand how these novel soil health indicators vary across different farms and soil types and how to translate soil health results for farmers in a way that can inform soil health management and broader sustainability goals. Finally, this study highlights that while soil health research has widely expanded in recent years, much more work needs to be done in its translational science. In addition to studying soil health indicators, their sensitivity, and accessibility, researchers should continue to explore ways in which these indicators can be conceptually understood and practically utilized by farmers.

Acknowledgments

We thank participant farmers for engaging in this study. We also thank Steve W. Culman for initial input on early drafts of manuscript. Lastly, we'd like to thank the internal funding sources at The Ohio State University for supporting this work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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