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Improving soil health

Edited by Professor William R. Horwath
University of California-Davis, USA

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Soil health: definitions, history, key concepts and hurdles

Michelle M. Wander, University of Illinois at Urbana-Champaign, USA

1 Introduction

1.1 Challenges of normative science

Contributors to this text were invited to review topics related to soil health defined as 'the continued capacity of soil to function as a living ecosystem able to deliver a range of ecosystem services that sustain plants, animals, people and the environment in which they live'. As such, soil health is not distinguished from soil quality, with definitions of both emphasizing the living and dynamic nature of soil and associating interactions between its physical, chemical and biological properties with soil functions that underpin services (Doran and Parkin, 1994; Karlen et al., 1997). Both terms are normative and utilitarian and have been criticized for their diffuse nature associated with reliance on values-based judgment of non-subjective measurements that are made based on land use, land type, prioritized soil functions and context for application (Davis and Miller, 2000; Letey et al., 2003). This means quality and health will vary with a perspective that depends upon whether they are applied to cultural, aesthetic, industrial and ecosystem services that extend beyond the scope of agriculture (FAO, 2015). Even though this text will prioritize the productive function and provisioning and sustaining services needed for food and fiber production to narrow criteria for attribute evaluation, this alone cannot resolve the subjective and at times contradictory aspects of these concepts' application.

Patzel et al. (2000) argued for greater clarity and consistency in the use of the two terms, *quality* and *fertility*, by both ley and scientific communities

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and concluded that making distinctions between these terms is helpful to both audiences by articulating concepts and acknowledging frames of reference. They also noted that while the concept of soil fertility is quite definite, it is dispositional or 'concealed' because judgments of what is, or is not, fertile are site specific. Additional weaknesses in the concept of soil quality were associated with undefined objectives and reliance on 'extensional definitions' that assert associations or linkages between properties and functions without providing sufficient evidence or specifying context. Schjønning et al. (2004) suggested that the emergence of the soil quality paradigm changed society's expectations of the scientific community by asking researchers to be conscious of societal priorities and their own values and goals. They noted soil quality and health are examples of reflective science, wherein the observer's efforts influence the object under consideration because research is undertaken within a cognitive space consisting of observational components that apply accepted methods within a civic setting for which the research is relevant using intentional processes developed to specify and then ideally satisfy goals tied to values.

Known challenges associated with the public's ability to place value judgements on soil indicator status and balance tradeoffs to determine how to use soil resources to appropriately meet societal needs (Patzel et al., 2000) must be addressed by structured steps that are not only reproducible and transparent but also acknowledge subjective, context-specific aspects of the work. While participatory research methods have been widely used in soil health research to satisfy these expectations (Andrews et al., 2003; Wander et al., 2002), it may be helpful to make a clearer distinction between soil quality and soil health to add clarity and transparency to a process that includes stakeholders in the process of assessment (Wander et al., 2019). Doran and Zeiss (2000) made this distinction noting soil health, defined as the capacity of soils to function, can be assessed using indicators of soil quality. By clearly associating soil quality with indicators used to assess soil condition and soil health with interpretive frameworks used to make judgments we can separate the scientific and socio-technical components of subjective health assessment. Distinctions between terms used by research communities that are delineated by expertise, location, and focus are made to define and shape the scientific discourse (Foucault, 1970). For example Grimm and Wissel (1997) found it beneficial to distinguish between terms used to describe ecological stability to efficiently communicate needed technical detail but that was harmful when distinctions reduce shared understandings. Of course, academic arguments like this are examples of privileged speech that are made moot when terms and related discourse are taken up by society (Landa and Angel, 2014). It is clear that the soil health framing is intuitive in nature and resonates with the public and this makes it well suited for social marketing purposes (Bouma and McBratney,

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2013; Brevick et al., 2019). Social movements that equate soil health with human well-being (Wander, 2009) may be vulnerable to bad-faith actors intending to exploit public sympathies. Whether or not this occurs will depend upon whether or not the sociotechnical systems we devise to achieve related goals can avoid creation of false narratives and unrealistic expectations (Giampietro and Funtowicz, 2020). Frameworks must provide the technical specificity and transparency necessary for unbiased assessment of soil capability and condition and then, honestly communicate that information through evaluative frameworks designed to set policy, back-stop product claims or guide management.

1.2 History and context

The soil health discourse results from concern for human well-being that has driven efforts to understand and characterize soil in terms of soil capability or fitness for use since the dawn of civilization (Dale and Carter, 1955; Hillel, 1991). Even though 'soil quality' and 'soil health' are often used interchangeably, 'soil quality' appeared earlier and has been used with greater frequency in the scientific literature (Fig. 1). Liu et al., 2020 suggest that efforts have been focused on the USA and that there has been limited international collaboration. Their findings are at odds with this review which suggests there has been global interest in convergent, synergistic scientific histories. Efforts to evaluate the soil resource and encourage its stewardship pique in response to historical events that have caused economic insecurity resulting in resource exploitation. This was the case in the USA in the 1930s when economic depression, drought and westward expansion produced threats to soil health that were addressed

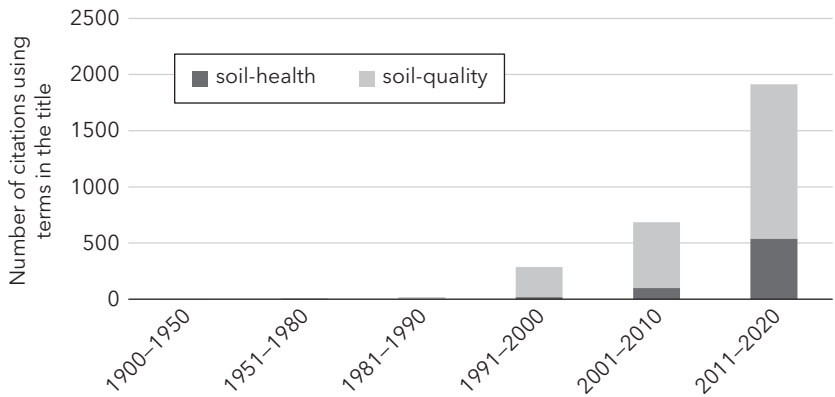

Figure 1 The increase in the number of citations using the terms 'soil health' in black or 'soil quality' in the article's title. These were recovered in the literature covered in the Web of Science.

by governmental action (Worster, 2004). During the first half of the twentieth century, references to both quality and health were being made globally to broadly consider plant–soil interactions and land capability classification. For example, Schultz (1925) used soil quality to understand the distribution of vegetation in South Finland and, Hoon and Dhawan (1950) used patterns in vegetation to delineate soil quality in India. The concept of soil quality was used to classify Esthonian (Zimmerman, 1939) and German soils (Wolff, 1939). Forbes (1928) delineated soil quality based on suitability for food or timber production in the USA in an article that challenged the notion that all arable land should be used for food production. Unfortunately, the notion that the most heavily timbered soils were the most fertile was imported from Europe and it took decades for this to give way to the recognition that US grasslands and oak openings were more productive and thus had greater soil quality from an agricultural perspective (Peters, 1973). Even though the fact that soil quality is multivariate, site and context specific has been emphasized repeatedly, this crucial point is constantly being overlooked. Whether this is an example of intentional 'bypass' by the soil science community that was cited by Baveye (2020) is not clear. What is certain is that without specificity useful applications of soil quality for soil health assessment are impossible.

Beginning in the 1980s soil quality was invoked globally in association with environmental concern with resource inventories shifting in focus to consider management and remedy environmental problems (Breeuwsma et al., 1986), assess risk from erosion (Yassaglou and Kollias, 1989; Urzelai et al., 2000) and realize sustainable development goals (Wilson, 2000). An uptick in interest coincided with soil degradation rates that increased in the USA in the 1970s and 80s with the opening of global agricultural markets and industrialization of agriculture (Debailleul, 1990; Lekkerkerk et al., 1990). This was followed in the 1990s by disruptions in the agricultural sector in Eastern Europe resulting from the breakup of the Soviet Union that raised environmental concern and interest in soil quality (Davis and Miller, 2000). Historical forces that have accelerated soil degradation fostered the emergence of soil quality as a distinct scientific object by the end of the twentieth century to pursue the simultaneous goals of increased or sustained production and the reduction or alleviation of environmental harm (Tilman et al., 2002; Schjønning et al., 2004). This objective arose in part to address perceived shortcomings of soil-fertility-based management that was focused too narrowly on soil chemistry and production (Letey et al., 2003). Soil quality and its attendant stewardship goals were quickly deemed to be essential for food security and successful ecological intensification needed to sustain or increase yield (Cassman, 1999). It was also referenced in association with other efforts to use soil properties to set standards for environmental cleanup (Siegrist, 1990), steward North American forests (Paige-Dumroese et al., 2000) and produce frameworks

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for 'Soil Care' (Stengel, 2000; Dumanski and Pieri, 2000). In such framings, soil quality can be seen as an addition to the well-established concept of soil capability classification. Soil quality adds consideration of land condition through the use of dynamic soil properties to try to optimize land use based on science (Steinhardt, 1995). Efforts have sought to use indicators associated with capability and condition at national and even global scales for decades (e.g. Gerasimov, 1983; Cox, 1995; Schipper and Sparling, 2000; Krüger et al., 2018).

The number of English language articles using soil quality and soil health in their titles has continued to increase at the pace of 100- and 500-fold during the last 20 years (Fig. 2). The number of peer-reviewed articles using 'soil' in their titles only doubled in the 90s and tripped in the 2000s in comparison with 1981–1990, suggesting publication access cannot explain the rapid increase in the use of these terms. A similar search for 'soil security' recovered only one paper published before 1950 and 30 between 2011–2020 using this term in the title. Increased international concern for soil quality and degradation resulted from increased awareness of the finiteness of arable land, projections for population growth and economic development and the recognition of the serious and immediate need to mitigate climate change (Gomiero, 2016; Karlen and Rice, 2015; Amelung et al., 2020). Interest in common global standards for indicators that began decades ago (Hortensius and Welling, 1996) has grown in kind (FAO, 2015).

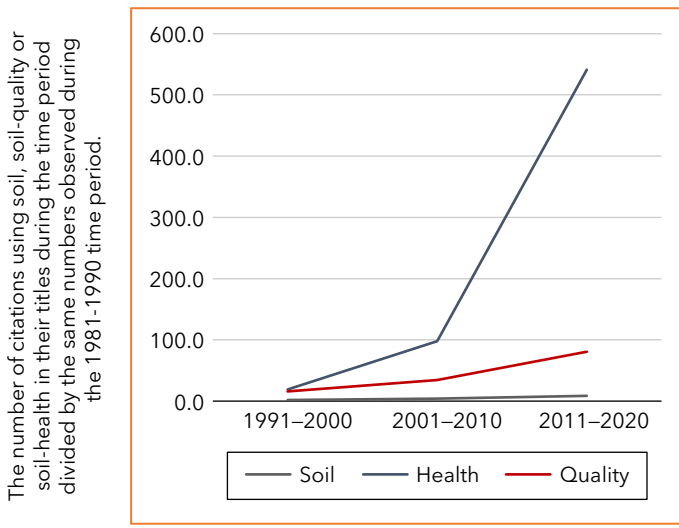

Figure 2 The increase in the numbers of manuscripts recovered using soil, soil-health or soil-quality in their title using Web of Science compared to the 1981–1990 period.

2 Evolving methodology

2.1 Multi-step process

Research efforts continue to address all aspects of indicator development including improvement of methods. Thiele-Bruhn et al. (2020) recently called for standardization of methods suitable for ecosystem service assessment endorsed by the FAO and UN, that consider soil microbial functions, including nutrient cycling and greenhouse gas emission, pest control and plant growth promotion, carbon cycling and sequestration, as well as soil structure development and filter functions. The criteria they outlined for indicator selection continued to include practicality, relevance and sensitivity judged subjectively by experts using methods that are generally consistent with the procedures and conceptual framing proposed by Andrews et al. (2002, 2004). Those procedures include indicator development, selection, interpretation and format for use-dependent applications with indicator scoring being related to performance or attributed based on inherent potential.

2.2 Indicators and key concepts

Reviewing a variety of approaches to develop and deploy indicators for agriculture Van der Werf and Petit (2002) separated soil properties or processes into 'means' (aka practice-based) indicators and 'effects'-based indicators associated with soil function. While some indicators, like water holding capacity or soil organic carbon, can be directly equated with services like water supply or carbon sequestration, the functions of many indicators are only broadly or indirectly associated with services. Soil organic matter and related qualities (e.g. C/N in Southeast Asian forest (Yamakura and Sahunalu, 1990), humus energy content (Kozin, 1990) and soil-dwelling arthropods (Reddy, 1986)) have long been recognized as useful integrative proxies that can aggregate information about multiple soil characteristics into one variable associated with shifts in carbon and nutrient cycles (Bailey et al., 2018). Emphasis on tight nutrient cycling is central to the soil health paradigm as it distinguishes soil health from fertility and associates these qualities with natural, undisturbed systems and biotic integrity (Wander, 2009). Accordingly, many biochemical assays, including extracellular enzymes and biotic indicators, are pursued as integrative assays for nutrient cycling, decomposition, pest suppression and plant resistance to stress (Burns et al., 2013; McDaniels et al., 2014; Ouyang et al., 2018; Larkin, 2015; Neher and Barbercheck, 2019; Tahat et al., 2020). These and other works continue to evaluate responsiveness to management and ways to establish functional value using indices that consider diversity and nutrient richness (Singh et al., 2012; Griffiths et al., 2018; Ney et al., 2019) as

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well as resistance and resilience (De Vries et al., 2012). Despite their proven value biota other than bacteria remain underused in soil health applications (Geisen et al., 2017). Much of the emphasis remains on the development of high-throughput microbial assays and 'OMICS' with work remaining in the comparative mode to understand the assay by drawing samples from locations under contrasting management or land use. Besides developing targeted approaches for the isolation of microorganisms from the soil, which allows a classical taxonomic assignment of genotypic and phenotypic traits, novel approaches integrating metagenomic datasets with other types of data such as metabolomics and abiotic factors will add insight into the workings of the microbiome (Feng et al., 2016). Unfortunately, many studies continue to rely on extensional definitions asserting relationships between diversity, richness and evenness or community composition resulting from management with nutrient cycling, plant growth promotion (Hartmann et al., 2015; De Curato et al., 2020). Ideally one could audit the community status of the system in relation to restoration targets and the effectiveness of management interventions and, shifts in the community or indicator status would be related to performance or enhancement of the rate of recovery of degraded systems (Harris, 2009). While this concept and aspiration are widely embraced, few works have meaningfully related microbiome attributes to system-level phenomena and relationships between omics, including sequence-relative abundance and function, unfortunately, remain obscure (Bailey et al., 2018). Efforts continue to strive to overcome taxonomic barriers and categorize soil microorganisms based on their ecological strategies associated with functional attributes but contend with the fact that despite the ever-growing sequence databases, marker gene, genomic and metagenomic analyses, most metagenomic reads cannot be assigned to a function and most soil microorganisms remain undescribed (Fierer, 2017).

Typically, the quantity, composition or process rate representing the 'effects' of management are commonly associated with soil services including nutrient cycling through correlation (Doran and Parkin, 1994; Andrews et al., 2002). For example, a recently developed multi-enzyme assay (Acosta-Martinez et al., 2019) was validated by demonstrating it appropriately ranked nutrient cycling status of soils under aggrading or degrading management. While meta-analytic work can confirm broad relationships between indicators, organic matter and nutrient abundance (Wang et al., 2018; Chen et al., 2018) much work needs to be done to associate indicators with services in a trustworthy, site-specific manner. Effects-type indicators, that relate indicators to desired outcomes, are attractive proxies because these can allow growers to select among practices to determine how to achieve goals based on their farming system, location and market contexts (Wander et al., 2002; Van der Werf and Petit, 2002). A drawback of effects-based indicators relative to the more general means- or

practice-based measures is that they require more intensive data collection and so are relatively costly and difficult to validate. Effects-based indicators have long been prioritized for hands-on applications by farmers or technical advisors. Efforts to develop applied tests that could help farmers relate soil quality to productivity that began in the late 1970s (e.g. Geyer et al., 1980) and identify a useful subset of indicators continue to be a priority (Mei et al., 2019; Xia and Wander, 2021). Whether or not the information they provide is of enough value to farmers remains an open question. It may be that transaction costs could be lowered enough to help farmers use soil information in the way envisioned many decades ago (Zusevics, 1979) by using technologyies that reflect land capability (Quandt et al., 2020).

Schjønning et al. (2004) prioritized interpretation of indicator response to management and asserted that management-based, not indicator-based, thresholds must be established to embed ethics into decision making to successfully implement the soil health concept. These types of means, or practice-based indicators, are well suited for policy-focused applications, conservation ranking and product valorization when adequately tied to services. Efforts attempting to relate indicator response to management use a wide variety of statistical techniques (Bunneman et al., 2018). Responsiveness to management is most often studied by comparing plots in replicated trials or multiple sites, including farm fields, or areas under different use or management using 'space for time substitution' that assumes qualities were initially similar. Samples taken from the same location separated in time are often assumed to be the best way to separate the influences of management and soil change or development. Unfortunately, this kind of comparison is much less common and can be problematic if care is not taken to prevent false equivalencies caused by slight differences in sampling, handling, processing or analytical methods. Meta-analytic studies comparing indicator status under contrasting management are commonly used to rank practice efficacy (Ugarte et al., 2018) and identify indicators that can discriminate among land-use histories (Lori et al., 2017). Unfortunately, few studies contextualize indicators or collect co-variates need to appropriately reward or target management through any mechanism by allowing users to separate management effects from uncontrollable or unchangeable system factors (Halberg et al., 2005). Extrapolation of services associated with management practices can be risky and when overextended can undermine the veracity of stewardship claims (Chabala et al., 2020).

2.3 Site specificity and resistance and resilience

Soil quality and health assessment struggle with the need to contextualize information and establish viable reference states. The environment or habitat provided by soils' physical and chemical structure is assumed to enable

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or constrain biological response to perturbation and thus, collectively determine soil stability, where resistance and resilience are governed by soil physicochemical structure acting through its effect on microbial community composition and physiology (Doran and Zeiss, 2000; Griffiths and Philippot, 2013). This conceptualization includes resistance and resilience as key criteria for soil quality and soil health assessments (Doran and Zeiss, 2000; Andrews and Carrol, 2001; Seybold et al., 1999). Related assessments commonly presume an economy of nature associated with tight nutrient cycling resulting from diversity and stability. This nature-based conceptualization treats non-managed or natural conditions as the ideal that serves as a baseline for comparison. Soils' intrinsic potential has often been assessed using data taken from soils maintained under natural or undisturbed land cover, typically grasslands or, by comparing the status of soils managed using best or better practices with controls managed using standard or conventional practices. Stability framings such as this are often challenged due to their vagueness and because they invoke the 'organismic theory of ecology' which relates communities' structure and function to idealized states (e.g. Clements' idea equilibrium state) that are not representative of reality and so widely criticized if not fully rejected by the scientific community (Ehrenfeld, 1992; Rapport et al., 1998). Microbial biomass-size, diversity or community evenness are examples of biotic indicators routinely assumed to be positively related to soil function and health including soils' productivity function (Crowder et al., 2010; Wittebolle et al., 2009). Over-generalization of these kinds of interpretive assertions is a common problem as site, land-use history and scale are all needed to constrain the domain of validity of stability statements (Grimm and Wiessel, 1997). Despite these weaknesses and the fact that drivers of microbial community stability and ability to resist or recover from disturbance remain poorly understood, the association between resilience, microbial community composition and soil capacity to function persists (eg: Allison and Martiny, 2016; Shade et al., 2012).

2.4 Emerging concepts

Fortunately, we are gaining insights needed to manage ecological systems and their biotic components intentionally with more basic research. Functional genes have usefully revealed the influence of cover crop mixes and methods of termination on ammonia oxidizers and denitrifiers (Romdhane et al., 2019). We have modest confirmation of associations between cover crop biomass, taxonomic (species richness) or functional (legumes vs. non-legumes) diversity and cover crop mixtures (Finney et al., 2017). The growing interest in the use of functional taxa that endophytes, symbionts, pathogens, and plant-growth-promoting rhizobacteria provide useful information (Philippot et al., 2013) is paralleled by a rising interest in the larger community of soil microorganisms

or soil microbiome (Chaparro et al., 2012). The plant microbiome has emerged as a fundamental trait that includes mutualism enabled through diverse biochemical mechanisms first revealed by studies of plant-growth-promoting and plant-health-promoting bacteria (Bulgarelli et al., 2013). Our ability to understand how plants recruit protective microorganisms and enhance microbial activity to suppress pathogens in the rhizosphere has begun to provide some mechanistic insights into theories proposed decades earlier (Berendsen et al., 2012; Philippot et al., 2013). This includes management of plant-growth-promoting rhizobacteria (PGPR) that colonize roots and mote phytohormones and other signals that enhance lateral root branching and development of root hairs (Vacheron et al., 2013). Communications between plants that modulate interactions favor association with beneficial microbes when grown under stressful conditions (Rosier et al., 2016). A rhizosphere-focused paradigm that has emerged posits that individual functions are coordinated by the community through biochemical networks connecting hosts and associated microbes where plants and animals are interdependent entities or 'holobionts' (Bordenstein et al., 2015). Research by Mendes et al. (2011) identified bacterial taxa and genes involved in the suppression of a fungal root pathogen by coupling PhyloChip-based metagenomics of the rhizosphere with culture-dependent functional analyses a decade ago suggests that indicators might reveal the status of the holobiont. While this kind of knowledge is useful to have, it is unlikely to lead to soil quality indicators as they are currently conceived because molecular communications fluctuate in space and time with plant growth stage, interactions between plants and other species, management techniques and edaphic factors (Chaparro et al., 2012). In many ways, the soil-testing approach used to assess and manage soils is incompatible with understanding or management of these fine-scape processes or associated (Vestergaard et al., 2017; Baveye et al., 2018). Appreciation of co-evolution of crops and their holobionts (Peiffer et al., 2013) has made crop breeding and selection more promising targets for information use. Intentional efforts to determine how to select microbiome–host interactions employ basic principles of quantitative genetics and community ecology. Mueller and Sachs (2015) outline core concepts and suggest how to manage soils to facilitate coadaptation between plants and microbes to enhance useful productivity along with resistance and resilience of the desired community.

3 Soil health assessment

3.1 Scoring

After efforts have identified responsive indicators and selected them for use, the indicators are scored or evaluated in relation to one or more functions or

in relation to an acceptable reference state. Individual variables are commonly transformed to simultaneously rate and convert values into unitless scores that can then be combined into an integrated health index (Doran and Parkin, 1994; Liu et al., 2018). For example, Mukherjee and Lal (2014) followed standard steps when they developed a scoring function for soil productivity using the weighted additive method (Karlen and Stott, 1994; Amacher et al., 2007; Fernandes et al., 2011) that considered root development, water storage and nutrient supply in relation to crop productivity by deriving indicator scores using principal component analysis. The maximum yield observed was used as the reference state for functional scoring and this single dimension score does not distinguish quality from productivity and does very little to address health. Whether biotic indicators are judged through correlation in relation to the soil's intrinsic potential (optimum or maximum state based on inherent potential) or in relation to an established reference state, one must identify some kind of benchmark and interpret indicator status using objective criteria that are holistic. Thiele-Bruhn et al. (2020) suggest explicit consideration of indicator constancy and dynamic equilibrium and use of endpoints that represent a potential function of soil microorganisms (implying a reference) rather than the use of actual activity levels could improve indexing. Regionalized references tailored to cropping systems can provide reference states. For example, Krüger et al. (2018) used regional references to assess spatial and seasonal variability of biological indicators (soil respiration potential, microbial biomass carbon, microbial C/N ratio, net nitrogen mineralization, metabolic potential of soil bacteria, earthworm abundance, microbial quotient and metabolic quotient) in grassland and cropland soils in Belgium. That and other works suggest population-based approach may be superior to the use of natural or idealized reference states. Ideally, reference ranges for indicators can be established within cropland or other land-use types that consider not only spatial variability but also time and of course, depth of sampling.

3.2 Combining

Once vetted, individual indicators are often combined into indexes after transformation using a variety of statistical techniques. For example, Ritz et al. (2009) used a semi-objective logical sieve to reduce 183 possible candidate indicators to 17 genotypic-, phenotypic- and functional- variables for use in national-scale soil monitoring with scoring by experts and stakeholders performed using scientific and technical criteria. Repeated iterations allowed indicator scores and weightings to account for end-user requirements and expert opinion. Scoring methods can recognize the need for site-specific scoring that considers both inherent and dynamic properties. For example,

Vogel et al. (2018, 2019) propose a systemic modeling framework to couple reductionist yet observable indicators for soil functions with detailed process understanding. They propose that functional attributes can be explained by a network of interacting processes derived from scientific evidence, with the non-linear character of interactions leading to stability and resilience of soil function. Integration steps have begun to attempt to quantify interdependencies and tradeoffs between functions. For example, Vrebos et al. (2020) used DayCent to estimate model indicators to build crop-specific Bayesian belief networks (BBNs) to estimate productivity, climate protections, water protections and nutrient use efficiency and tradeoffs in function under current European Union conditions. Only relationships found to be plausible were retained after 'validation' by expert opinion. Algorithms used by BBNs can help capture the inductive inferences of stakeholders (Bonawitz et al., 2011) and provide a computational framework needed to compare the expected consequences of different types of management actions (Dorazio and Johnson, 2003). While, In theory, BBNs, which are a graphical network of nodes linked by probabilities, can help users make more informed and disclosed decisions about resource management (McCann et al., 2006), caution must be applied when they are based on limited or synthetic data that is also not proven (Marcot et al., 2006). Some fear the subjective aspect of BBNs can potentially obfuscate and embed bias in a way that is difficult to remove (Schweizer, 2019); however, this is one of the few ways to enable valid scientific quantification of perceptions of soil functions /services (including uncertainties) (Baveye et al., 2016). Baveye et al. (2016) recommend the use of BBNs with deliberative decision-making methods and note that the literacy of participants is critical to effectively and ethically rank services. Correlation and co-occurrence analyses and multi-criteria decision support systems are examples of useful techniques (Zwetsloot et al., 2020). Before decisions can be made, estimates of services and preferences should be provided (Coker et al., 2019) to parties engaged in ranking and weighting activities but unfortunately, location and system-specific information about services supplied by practices or policies are commonly inadequate.

4 Conclusion

Even though soil quality and health continue to receive academic critiques of their utility and scientific validity, the public and private sectors have rallied around the soil health concept as a way to help address food security, environmental degradation and climate change. Whether or not indicators of quality or soil health assessments prove to be useful or, instead consume resources better spent on other approaches may depend upon whether proponents can better clarify their objectives to apply indicators with functional relevance for specific biophysical and civic contexts. In order for effects-based

indicators to find commercial success and be useful for valorization of individual fields or farms, extensional definitions that assert nebulous notions of diversity and stability must be replaced with appropriate references states and well-articulated relationships between indicator status and nutrient use efficiency, plant health and pest suppression. These understandings must be combined with up-to-date agronomic information and integrated nutrient management strategies that improve not only soil quality (Wu and Ma, 2015) but also productivity and other services. Improving data access through digital platforms and new technologies may be able to lower both the transaction and monetary costs associated with historical land capability classification to make information useful for site-specific applications. Calls for standardized methods and national or even global commitment to this approach to support ecosystem service markets first need to overcome our limited or incomplete understanding of inherent sensitivity, responsiveness to management and functional relevance of many indicators (Römbke et al., 2018). Very few efforts proceed to establish benchmarks that provide contextual information, delimited by space and land use in sufficient detail to reflect the inherent potential of a site in its optimum status and allow comparison with the present condition. Calls for policies that promote soil stewardship through practices that build soil organic matter and presumably other soil health attributes (e.g. Gomiero, 2016; Amelung et al., 2020) need to more than just acknowledge the need for contextualization. Efforts to implement policy or set targets often fall back on expert opinions and assertions about the benefits of different farming practices despite full knowledge of site-based variability. Analytical approaches like BBNs and deliberative frameworks might include procedures for a clear record of the decision-making process, flexibility in prioritization of function, and the ability to accommodate the inclusion of new or additional methods or indicators into the framework (Ritz et al., 2009; Baveye et al., 2016).

5 Where to look for further information

- Nature Reviews: Plant microbiome. https://www.nature.com/collections/jcbagaigaa.
- Standards by ISO 190: Soil Quality: https://www.iso.org/committee/54328/x/catalogue.
- Natural Resources Conservation Service Soil Health: https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.

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