Towards a farmer-feasible soil health assessment that is globally applicable

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Acknowledgements: This work was supported by a NERC (Natural Environment Research Council) Doctoral Training Partnership grant (NE/S007407/1), Syngenta Crop Protection AG and the ClieNFarms project which received funding from the European Union's Horizon 2020 Societal Challenges Program under the grant agreement No 101036822. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

Keywords: minimum data set, soil assessment, soil health, soil management, decision support

Highlights:

- We need farmer-feasible soil health assessment (SHA) for global soil security
- Most existing SHAs are costly and only calibrated for some agro-ecological contexts
- There is a gap for practical SHA linking management to soil health outcomes
- Farmer-centric SHA should recognise farmer expertise and consider visual indicators
- We propose assessing information benefit of soil indicators to find sufficient SHA
- ~~We need farmer-feasible soil health assessments to support soil management~~

- ~~Existing assessments are too costly for many farmers, and not locally parameterised~~
- ~~We must reduce complexity and increase applicability of minimum datasets~~
- ~~Farmers must be included in assessment scoping as they are both experts and users~~

1. Abstract

Globally, agriculture has had a significant and often detrimental impact on soil. The continued capacity of soil to function as a living ecosystem that sustains microbes, plants, and animals (including humans), its metaphorical health, is of vital importance across geographic scales. , Healthy soil underpins food production and ecosystem resilience against a changing climate.

This paper focuses on assessing soil health, an area of increasing interest for farming communities, researchers, industry and policy-makers. Without accessible and reliable soil assessment, any management and interventions to improve soil health are likely to be sub-optimal. Here we explore available soil health assessments (SHAs) that may be feasible for farmers of varying income levels and suitable for broad geographic application.

Whilst there is a range of existing approaches to SHA, we find that no one framework currently meets these broad aims. Firstly, reliance on expensive and logistically complex laboratory methods reduces viability and accessibility for many farmers. Secondly, lack of defined indicator baselines and associated thresholds or gradients for soil health prevents the assessment of soil measurements against achieving optima for a given set of local soil-climate conditions. Since soils vary greatly, these baselines and thresholds must be defined considering the local biogeographic context; it is inappropriate to simply transfer calibrated information between contexts. These shortcomings demand progress towards a feasible, globally applicable and context relevant SHA framework. The most feasible SHAs we identified were developed locally in conjunction with farmers, who have been repeatedly found to assess the health of their soils accurately, often using relatively simple, observable indications. To progress, we propose assessment of which indicators add information to

a SHA in local contexts, with a focus on sufficiency, to reduce data burden. Provision of a standardised protocol for measurement and sampling that considers the reliability and accuracy of different methods would also be extremely valuable. For greatest impact, future work should be taken forward in a cross-industry collaborative approach between researchers, businesses, policy makers, and, above all, farmers, who are both experts and users.

2. Introduction

Global food demand will increase by up to 62% between 2010 and 2050 due to population growth, climate change and other societal drivers (van Dijk et al., 2021), necessitating a near doubling of crop production (Tilman et al., 2011). This increase in pressure on land resources threatens to drive land degradation and, consequently, negatively impact a range of ecosystem services including local food production (Hossain et al., 2020).

Soil is a critical component of many ecosystem services (Pereiera, 2018). It is crucial for carbon sequestration, water purification, biodiversity conservation, nutrient cycling, plant nutrition, and climate regulation (Brussaard, 2012; Bünemann et al., 2018). It is therefore detrimental for both food production and wider ecosystem functioning that over a third of the world's soils, and over half of agricultural soils, are degraded (Davies, 2019; FAO & ITPS, 2015; Baritz et al., 2017). Whilst soil is the largest terrestrial carbon sink, soil disturbance in agriculture has accelerated the mineralisation of soil organic matter (SOM), making soil a significant net source of greenhouse gas emissions (Lal, 2018; Grassi et al., 2022) and lowering the carbon available for other ecosystem functions. Managing agricultural soils to function well now and into the future is a priority at all scales; for farmers, policy makers and wider society.

The terms soil health and soil quality are both commonly used to refer to the ability of soil to function as part of its ecosystem, be it managed or natural (Bünemann et al., 2018; Rinot et al., 2019; Lehman et al., 2015; Jian et al., 2020). Identified soil functions (Table 1) all depend on soil’s biological, chemical, and physical properties (Guo, 2021), which vary naturally across ecosystems due to climate, mineralogy and biodiversity, and are further altered through management. In this paper, we will use the USDA definition of soil health (Table 1) as it is widely adopted by a range of stakeholders. Additionally, whilst organic soil management is of critical importance (Joosten et al., 2016), we mainly focus on mineral soils in our conceptualisation of these soil functions.

Functioning, healthy soils are more stable and resilient to physical, biological and chemical stressors, with reduced risk of soil erosion and improved aeration and water infiltration (Bot and Benitez, 2005), minimising runoff. They have greater resistance to, and recovery from, flooding and drought, and are more capable of functioning as a pollution buffer or filtration system (Cachada et al., 2018). A living terrestrial ecosystem relies on nutrients provided by soil which sustain, and are sustained by, diverse soil organisms (Lehman et al., 2015; Fall et al., 2022; Powell and Rillig, 2018).

***Table 1**: definitions used in different jurisdictions and associated soil functions. These two lists of soil functions show significant, if not complete, overlap. Whilst the NRCS definition includes physical stability, and mentions pollutants explicitly, the Landmark 2020 approach calls out climate regulation and carbon sequestration, as well as productivity as a service to humans.*

	USA: NRCS-USDA	Europe: Landmark 2020
Term	Soil health	Soil quality
Definition	*the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans* (NRCS-USDA, n.d.*a*).	*the degree to which a soil can perform its functions* (Landmark 2020, 2018).
Soil Functions	• Nutrient cycling • Creating physical stability and support • Filtering and buffering potential pollutants • Sustaining plant and animal life • Regulating water (NRCS-USDA, n.d.*a*).	• Primary productivity (of food, feed, fibre and fuel) • Water purification and regulation • Climate regulation and carbon sequestration • Soil biodiversity and habitat provisioning • Provision and cycling of nutrients (Schulte et al., 2011 and Bouma et al., 2012 in Schulte et al., 2014)

Annual cropping systems with monoculture or deep tillage can deplete soil health over time, whereas pasture and forage systems tend to have a less negative, or even positive, impact (Karlen et al., 2017; Nunes, et al., 2020). Whilst overall impacts of agriculture to date have been detrimental for soil and soil carbon, management decisions (e.g. on inputs, soil cover or use of machinery) can be made to protect and improve soils (Lal, 2004; Lehmann et al., 2020, Karlen *et al.,* 2019). It can be difficult to manage adaptively for soil health without monitoring progress through quantitative assessments. Soil health assessment (SHA) is therefore a key tool to help inform agricultural management for better soil outcomes. It is important that farmers and land managers globally can assess and understand the impact of different management practices on the health of their soils. This knowledge can be used to inform areas such as farm management decisions, the sustainable sourcing strategies of supply chain actors and policy driven payments for ecosystem services.

In recent decades, there has been an exponential growth in publications that use the term ‘soil health’ (Janzen et al., 2021 and references therein), encompassing parallel discussions in scientific communities about the concept and its application (e.g., Lehmann et al., 2020; Powlson, 2020; Baveye, 2020; Janzen et al., 2021; Davis et al., 2023). Soil health is essentially a metaphor without a single agreed definition and cannot be directly measured. Compared to alternative terms like soil quality and soil fertility, the health metaphor can bring widespread appreciation of an ecological systems perspective on soils, looking beyond a production perspective and positioning soil as a common good (Janzen et al., 2021; Lehmann et al., 2020). Baveye (2020) warns that any opportunity to unite for soil health may be wasted without an accepted definition, and fully scoped approaches to measure it. We do not necessarily position this paper as a further comment on the soil health concept but acknowledge the nuances alongside the potential of the term.

Against this backdrop of ongoing discourse in science, there have been several recent reviews on the topic of soil health quantification and assessment (e.g., Guo, 2021, Rinot et al., 2019, Bünneman et al., 2018, Lehmann et al., 2020), and activity amongst policy makers, land managers and farmers is gaining momentum (European Commission, 2021). Existing researcher-led approaches to SHA are often comprehensive and may rely on access to analytical facilities. To achieve widely desired outcomes for soil and ecosystem services, there is a clear need for a globally scalable, feasible and affordable framework for practitioners to assess soil health and act on the results. In this paper, we pursue a SHA that fits these combined criteria, first by reviewing existing SHAs and then by discussing the remaining obstacles to establishing a new framework that enables global soil challenges to start to be effectively addressed.

3. Criteria for the target Soil Health Assessment Framework

3.1. From soil indicator measurement to Soil Health Assessment

Since soil health cannot be measured directly per se, SHAs rely on a combination of measurable indicators to estimate how well the soil functions. An ensemble of indicators that measure, or relate to, different soil properties is needed to encompass a wide range of soil functions and thus reflect overall soil health and changes therein (Doran & Parkin, 1996; Bünemann et al., 2018; Rinot et al., 2019; Guo, 2021).

Since natural soil properties and their context vary, soil health may be considered continuous and relative, rather than absolute. Moving from measuring soil indicators *in situ* to creating a SHA requires an appropriate context-specific baseline, representing ideal potential indicator values (Moebius-Clune et al., 2016; Lehmann et al., 2020). Threshold levels or continuous gradients for poor and/or good soil health can then be defined against that baseline. Whilst baselining is broadly out of scope for this review, we note that a baseline may be established by one of two approaches: (i) assessing conditions of the native undisturbed soil, or (ii) assessing conditions that maximise desired ecosystem services (e.g. production) (Doran & Parkin, 1994). Given a clear definition of 'native undisturbed', the former provides a fixed baseline and is simpler to conceptualise globally. The latter, while providing a more contextualised baseline for agriculture, requires assumptions on management- which would tend to differ geographically- and is more likely to change over time due to external factors. It also suggests that the primary function of soil is always production, which may be at odds with wider ecosystem functioning in some areas- such as forest soils in water stressed areas (Pereira et al., 2018).

Indicator measurements require a mathematical step to relate them back to reference values for healthy soils in a particular context. These can be used in a quantitative scoring system or a qualitative result (poor/good) relative to the defined baseline. These mathematical steps can be thresholds, linear gradients or curves. In much existing work, thresholds and critical indicator values for poor and/or good soil health are discussed and defined (e.g. Bünemann et al., 2018; Guo, 2021; Lal, 2016). Given our focus on providing decision support information we refer to thresholds more often, as they give a clear indication of where there is an issue to act upon.

3.2. Feasible for farmers

There is potential for farmers to manage soil health through different agricultural practices targeted at specific soil functions (Doran, 2002; Ros et al., 2022). This requires SHAs which can detect changes in soil functions as a result of management practices (Stott, 2019; Guo, 2021), but which are also feasible for farmers to carry out on their land and that produce data relevant for farm management decisions (Davis et al., 2023). The assessments must be practical to perform in terms of cost, time, and skills required for data collection and interpretation (AHDB, 2018; Stott, 2019; Lehmann et al., 2020). At the time of writing, global fertiliser prices are high and prompting renewed interest in soil diagnostics as a tool to aid reduction of input costs (Cavallito, 2022) as well as environmental impacts.

Currently, implementation of soil health assessment shows wide variation geographically. In the UK, one third of surveyed farmers do not conduct SHAs (Sizmur, 2016- unpublished) whilst in Africa, for example, the adoption of improved soil management practices (including Integrated Soil Fertility Management, which is underpinned by principles of soil health) is limited for smallholders (Klauser & Negra, 2020; Mugwe et al., 2019).

Lowder et al. (2021) estimated that there are over 608 million farms in the world. Around 85% are smallholder farms of ≤2 hectares where soil heterogeneity may be much greater than larger farms (Snapp, 2022). These small farms operate around 12% of the world’s agricultural land and are concentrated in lower income countries. Most farmers, therefore, do not manage large operations with budget for expensive soil analysis. On the other hand, many farmers have extensive knowledge of the land and soil they are working and apply this daily to secure their livelihood. Studies have shown that, whilst not standardised, farmers' interpretations of their soil health are broadly accurate (Entz et al., 2022; Head et al., 2020) and widely based on observable attributes such as structure, colour and yield (Eze et al., 2021; Mairura et al., 2007).

3.3. Globally applicable

The critical dependence of agri-food businesses on soil health is well understood. However, downstream processors and retailers depend on agriculture to supply their raw materials and are thus exposed to risks to supply when agricultural practices are unsustainable. Organisations further along the value chain are considering how to support producers in their supply chains to practice farming that protects and strengthens soils for the future (WBCSD, 2018; Head, 2019; Southey, 2020; Fact.MR, 2022). This has led to the establishment of several pre-competitive consortia and other initiatives to develop and apply indicator-based assessments of agricultural practices (e.g., Stewardship Index for Specialty Crops, 2022; Cool Farm Alliance, 2022; Field to Market, 2022). The risk to food supply, businesses and the environment has also led to soils being a policy priority across scales (e.g. Scottish Government, 2009; UN Convention on Biological Diversity, 2018; WBCSD, 2018).

Whilst the importance of managing soil health is widely recognised, wide application of indicator-based assessments to soil health is lacking. Other broad initiatives developed to support soil health through supply chains are often rule or practice based (e.g., Farm Sustainability Assessment, SAI Platform, 2018; Global Farm Metric, 2022), rather than being developed, quantitative methodologies.

There is interest in scoring systems that can be used by any farmer within any supply chain, regardless of product, geography, or scale. Since potential soil health is determined locally, 'global' in this context means at least multi-regional and not focused on the available resources or dominant management approaches of any one region over another. SHA frameworks may not require identical application in different contexts, but should contain logic and guidelines for consistent application.

3.4. Soil indicator requirements

We have outlined why it is important to create a globally-applicable SHA, which is also feasible for practitioners to measure regardless of operational scale, income, or management practice. Soil health indicators for use in such a SHA should satisfy four requirements (Table 2). When creating a SHA from individual indicators, the full set of indicators used should also cover all five soil functions (Table 1) and the three overarching soil characteristics (physical, chemical, biological), as information on any single soil function cannot adequately reflect changes to soil health or underlying causes (Guo, 2021). With the priorities applied here, we pursue a minimum data set (MDS) which is sufficient for meaningful SHA, yet parsimonious in terms of data burden.

Table 2 *Requirements for choosing soil health indicators (Based on Stott, 2019)*

Soil health indicator requirements	
Effectiveness	To support management decisions for soil health, the indicators used in the SHA must be sensitive to farm management on a short timescale (1-3 years) (Stott, 2019), and interpretable in relation to soil functions or conditions.
Readiness	The indicators must be relatively easy for farmers to measure *in situ* or readily collect samples and submit for analysis, and it must be viable for farmers (with possible support from extension services) on a per-sample basis regarding cost/time investment, and skills required (AHDB, 2018; Lehmann et al., 2020)
Measurement repeatability and sensitivity	Indicator measurement methods need to be precise enough to detect changes and robust enough to provide consistent results, on a scale that provides confidence in the implied impact of management on the indicator (Stott, 2019).
Decision relevance	The indicators need to be directionally understood (one of: more is better, less is better, an optimum value), have a definable range for poor/good soil health, and be improved by some management practice(s) (e.g., Lima et al., 2013; Moebius-Clune et al., 2016; Griffiths et al., 2018.)

4. Is a global, feasible and relevant Soil Health Assessment available for farmers?

4.1. Scientific research

Soil indicators are measured across science, technology, engineering, and mathematics (STEM) and humanities research. Studies evaluating land management practices that affect soil health tend to have a narrow focus on one or two practices (Stewart et al., 2018), and the choice of indicators is inconsistent. Stewart et al. (2018) reviewed 192 cover cropping and no-till studies and found that only eight of 42 indicators were included more than 20% of the time (Figure 1) and that there was little standardisation of methods and sampling. Soil organic carbon (SOC) and SOM (combined) dominated by frequency as they are deemed applicable to many soil functions (see Box).

Much of the agriculture-focused literature looking at soil health outcomes can fulfil stated aims by presenting separate indicator measurements without quantitative consolidation into any transferable SHA framework. Though many scientists are interested in combining soil indicators into a single soil health score, few scoring approaches exist (Lehmann et al., 2020) due to the complexity of representing all potentially relevant information across contexts, and also different emphases depending on local soil challenges and context. Soil health benchmarking supports the optimisation of efforts to improve soil health (Maharjan et al., 2020) and could support the expansion of geographical scope in scientific research by providing something to report against.

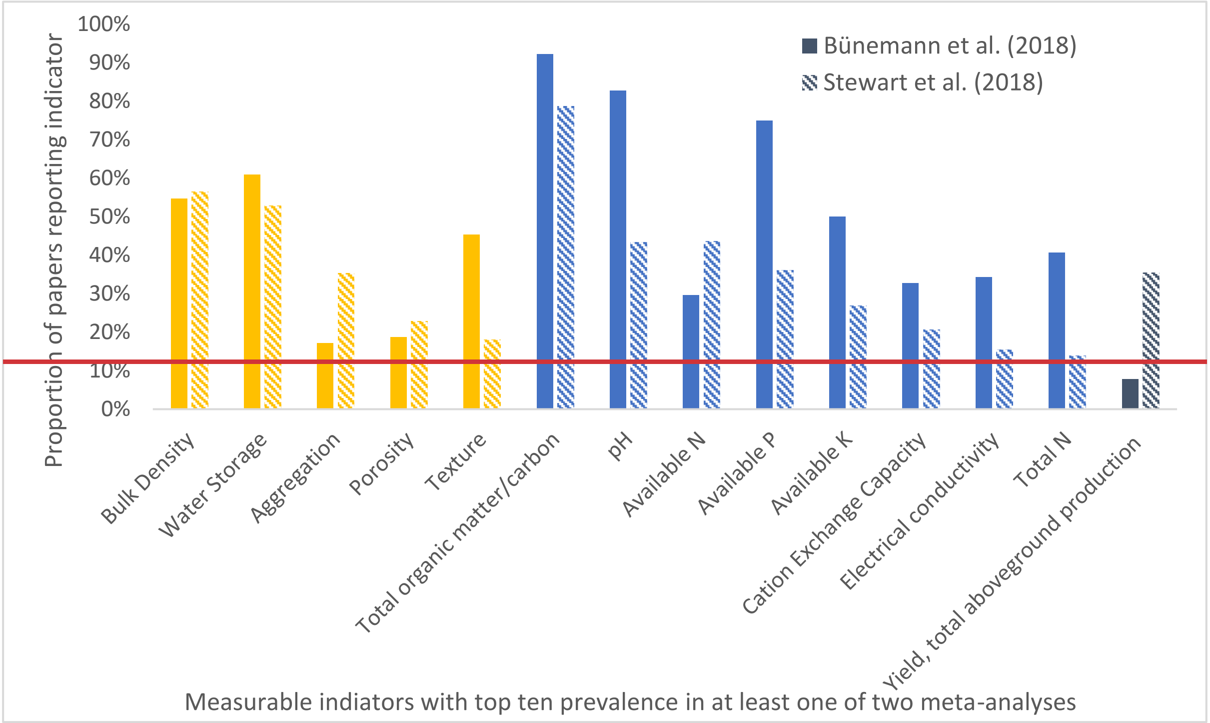
Moving beyond meta-analysis of indicator measurements, Bünemann et al. (2018) reviewed 62 studies proposing soil health MDS. The most common indicators were similar to Stewart et al. (2018) (Figure 1). The average number of proposed indicators was 11; usually too many to be practical and viable in the field (Bünemann et al., 2018). Importantly, however, the number of indicators is not the main determinant of feasibility for farmers; it is rather the cost (financial and time) and complexity of collecting data for specific indicators that prohibits use. Whilst we cannot precisely cost each proposed indicator for all farmer contexts, Supplementary Table 1 gives our estimated cost levels- Low, Medium and High, and we consider any requirement such as laboratory analysis or specialist equipment to have logistical considerations as well as financial cost.

In terms of decision support, of those indicators included in more than 20% of MDS, approximately half are relevant, sensitive, practical and informative (Lehmann et al., 2020). Most soil quality assessments are developed by researchers, either as primary or secondary developers, though they are often not the target end users (Bünemann et al., 2018). Government agencies have been involved in development and end use of SHA frameworks, whilst farmer organisations were rarely identified as major developers or end users by scientists.

Recently, the importance of biological indicators (for example, microbial biomass carbon, soil respiration or earthworm numbers) as part of a SHA has become clear, as they are key indicators of biodiversity underpinning soil processes (Lehmann et al., 2020; Nunes et al, 2020; Sarkar et al., 2022) and because they often exhibit the most rapid responses to management (Stewart et al., 2018).

Biological indicators can be linked to outcomes including nitrogen availability (Grandy et al., 2022) and water supply (Lima et al., 2013). However, biological indicators can often require more complex measurements and a deeper understanding for analysis, supported by recent advances in sequencing capabilities. This is not in line with the criteria for suitable indicators as listed in Table 2. Additionally, and relatedly, biological indicators are amongst the least measured (Figure 1; Stewart et al., 2018) and were completely absent from 40% of the MDS assessed by Bünemann et al. (2018). Biological indicators that are used often require new methods or are extremely specific (Bünemann et al., 2018).

Overall, studies relevant to SHA give an incoherent picture. There is consensus on the requirements for soil health indicators (Table 1; Lehmann et al., 2020), but these are applied differently by different stakeholders, whose local context informs their own tolerances and perspectives. Soil impact studies tend to be highly focused, rather than proposing broad classifications. There is some overlap in the indicators commonly measured in soil impact studies and those selected in MDS, with, two caveats: firstly, the underrepresentation of biological indicators; and secondly the lack of standardisation in measurement and sampling. From the perspective of farmers, MDS proposed in scientific papers to date tend to ask too much: a range of data points which often require specific expertise, equipment and/or analysis (Figure 1 and Table S1).


100%
90%
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70%
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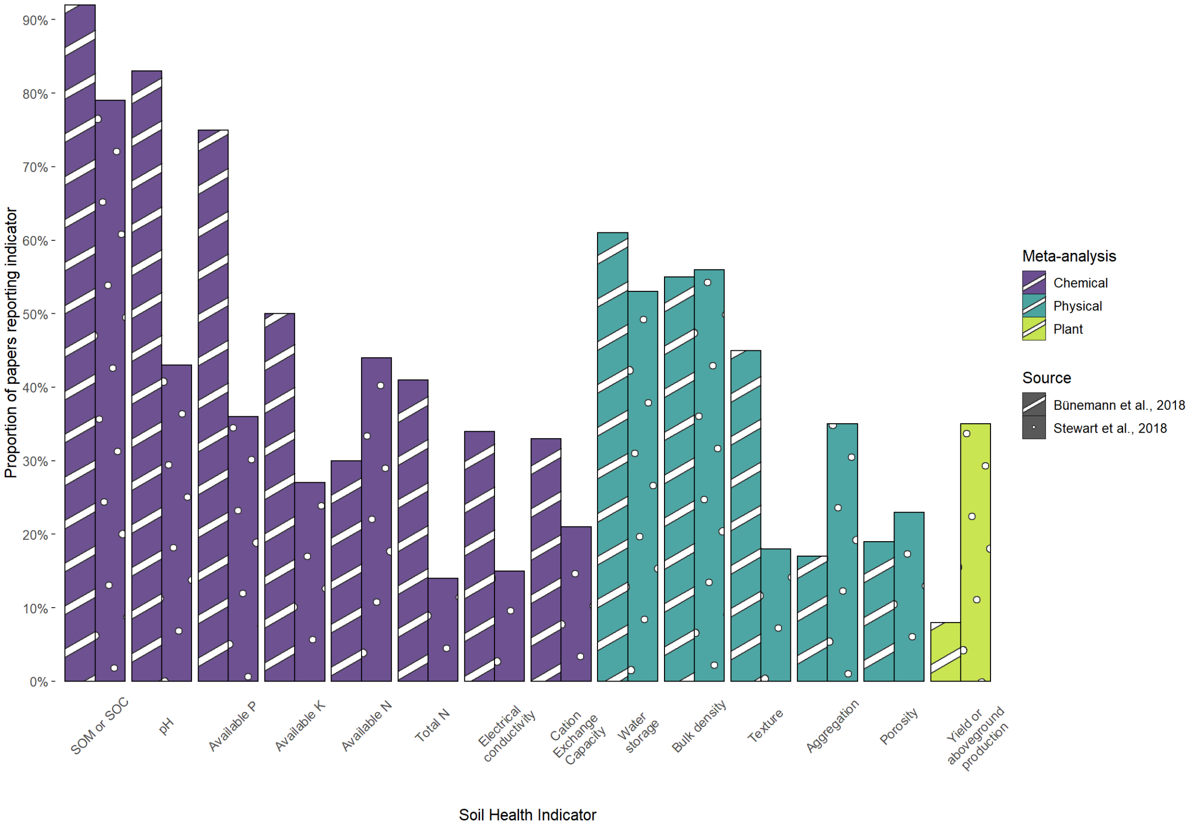
Proportion of papers reporting indicator
Bünemann et al. (2018)
Stewart et al. (2018)
Bulk Density
Water Storage
Aggregation
Porosity
Texture
Total organic matter/carbon
pH
Available N
Available P
Available K
Cation Exchange Capacity
Electrical conductivity
Total N
Yield, total aboveground production
Measurable indiators with top ten prevalence in at least one of two meta-analyses


90%
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10%
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Proportion of papers reporting indicator
SOM or SOC
pH
Available P
Available K
Available N
Total N
Electrical conductivity
Cation Exchange Capacity
Water storage
Bulk density
Texture
Aggregation
Porosity
Yield or aboveground production
Soil Health Indicator
Meta-analysis
Chemical
Physical
Plant
Source
Bünemann et al., 2018
Stewart et al., 2018

Figure 1 *Most prevalent indicators in two meta-analyses on soil assessment. Bünemann et al. (2018) looked at studies proposing MDS and Stewart et al. (2018) looked at indicators measured in crop management studies. These are indicators with top 10 prevalence in at least one of the two meta-analyses. Yellow = physical, blue = chemical, no biological indicators were present in this subset.*

Box: Soil Organic Matter & Carbon

SOM and SOC are most commonly utilised as part of a SHA (Figure 1). SOM is key to soil health due to its regulation of a wide range of soil characteristics and functions. Here we summarise SOM and SOC's roles in relation to soil functioning and other soil properties.

SOM is a mixture of plant and animal residues, products of chemical and physical processes and biomass of soil organisms (Bot and Benitez, 2005). Components of SOM can be functionally divided into groups depending on molecular weight. Whilst proportions of these compounds vary between soils, compounds of low molecular weight (e.g. glucose) are sources of easily accessible carbon for microbial communities, compounds with high molecular weight (e.g. lignin) are more resistant to microbial access. The main elements in SOM are carbon (C), nitrogen (N), phosphorus and sulphur, but C is most prevalent (0.5 – 0.58 g SOC (g SOM)$^{-1}$; Nelson and Sommers, 1996). In scientific literature, there is often a generalisation of SOC and SOM. For soil health purposes, SOM has clear physical, biological and chemical relevance. SOM conceptually relates directly to more functions than SOC, but they are both favoured indicators (Figure 1).

Compounds produced through SOC degradation bind soil particles, producing aggregates beneficial for soil structure (Bot and Benitez, 2005), reducing bulk density and increasing stability (e.g. Alvarez et al., 2013; Piccolo and Mbagwu, 1999; Fowler et al., 2023). SOC increases water retention, particularly in coarse soils, which can affect water availability (Manns and Berg, 2014; Weber 2023). More SOC increases infiltration rates due to the impact on bulk density (e.g. Ruehlmann and Körschens, 2009; Porzig et al., 2018). Overall, Alvarez et al. (2013) found SOM 'quality' is crucial for soil properties in general, but particularly for the infiltration rate in semi-arid areas with low SOC.

As SOM is mineralised by microorganisms, the elements become available as nutrients for plants and other soil organisms, supporting soil biodiversity. Whilst degradation is dependent on temperature, soil moisture, SOM composition (C:N ratio), soil microbial communities and vegetation, greater SOM generally increases overall nutrient availability and SOC increases microbial activity, encouraging degradation. SOC increases soil's nutrient holding capacity and reduces loss by leaching (Bot & Benitez, 2005). Given a pH within typical agronomic ranges, SOC increases CEC 1(Solly et al., 2020) and therefore retention of nutrient cations. Finally, by reducing bulk density and providing nutrients, SOC is associated with a greater number of earthworms in

4.2. Science-led methods

As identified in Bünemann et al. (2018), several science-led SHA frameworks exist that are designed for wide use and are accessible to the public. These tools tend to be based on MDS similar in scope to those defined above and offer a (mathematical) method to assess soil health from indicator measurements. Sometimes this is combined with provision of standardised indicator measurement services, which is a key benefit. Guo (2021) and Bünemann et al. (2018) give thorough summaries of the approaches available and their characteristics. Here, we briefly introduce three commonly used methods for illustration.

- Cornell's Comprehensive Assessment of Soil Health (CASH) (Cornell Soil Health Laboratory, 2017~~6~~) includes 12 soil health indicators, the majority of which are assessed in the laboratory from a composite soil sample (Guo, 2021; Moebius-Clune et al., 2017). A soil health score between 0-100 is calculated and associated with qualitative (low, medium, high) and traffic light (RAG) ratings. Congreves et al. (2015) developed a SHA for Ontario, Canada, building on CASH. At the time of writing, the basic analysis package at Cornell's laboratory costs USD $90 / sample (Cornell Soil Health Laboratory, 2022).
- A Solvita soil health assessment (Woods End Laboratories, 2021) is based on six indicators measured using equipment in the field and laboratory. Solvita field and laboratory indicator methods are widely cited in both scientific and grey literature, but only some geographies have parameterised ranges (US, Canada, some EU) to result in a SHA calibrated against regional expectations. At the time of writing, the Woods End Laboratory charges USD $45 / sample for basic analysis (Solvita, 2021).
- The Soil Management and Assessment Framework (SMAF) (Andrews et al., 2004) proposes a MDS based on management objectives and agro-ecological context. Users can utilise or ignore the suggested MDS, making comparison using SMAF inadvisable (Bünemann et al., 2018) and costs more variable.

These three SHA frameworks provide index scoring using calibrations specific for each agro-ecological/climatic context and are available only where these have been established. Those described were all developed in, and for, the U.S.A., which has the benefit of various well-maintained databases (e.g., SSURGO- Soil Survey Staff, 2019). They have been extended and adapted for use elsewhere where resources (data, finance, expertise) were available for calibration. The development of new scoring curves for each climate, geography and soil texture combination is possible, though resource intensive (Guo, 2021).

Also in North America, the Soil Health Institute (SHI) is spearheading the North American Project to Evaluate Soil Health Measurements (NAPESHM) to ‘identify widely applicable soil health measurements’ (Norris et al., 2020). A cross-industry workshop series identified 28 indicators for investigation. These indicators were put into ‘tiers’ based on the strength of their validation and acceptance as part of a SHA (Guo 2021). There are 19 Tier 1 indicators which have been widely accepted, though Stewart et al. (2018) note that earthworm tests are omitted and there is a general lack of biological indicators. More recently, SHI has proposed three focus indicators for North America and provided a fact sheet with information on how farmers should assess them (SHI, 2022). At the time of writing there is no proposed scoring system for these indicators.

Most of the methods and work cited here aims to suit a North American (often U.S.A.) context. The implications of this, considering our aims here, are broad. The soil types and climates considered are regional, as are the management considerations underpinning establishment and advice on these approaches. In addition to a geographically restricted parameterisation, CASH and Solvita have costs and analytical requirements associated with them that make them inaccessible for many farmers (we quote the costs at the source institution; also see Table S1). SMAF’s data burden can also be significant; data flexibility benefits are offset by the limitation they pose to comparability across contexts. By taking care of computation, these tools can present soil health results in interpretable ways. However, to ensure access to SHA for most farmers, it is necessary to reduce the data collection burden in terms of time, skill and cost whilst retaining a meaningful and robust assessment relevant across international farming contexts.

4.3. Farmer-focused methods

Farmer-focused SHA frameworks have been developed with an emphasis on measurement feasibility and decision support. Due to the complexity of distilling soil health into a truly parsimonious MDS, these tend to be local in geographical scope, and sometimes specific to production systems. Compared to science-led methods, these approaches are far more likely to have involved farmers in their development.

A study by Lima et al. (2013) compared soil quality assessments based on 29 indicators with a subset of eight of those indicators and with a further subset of four indicators selected independently by farmers. They found that the use of a smaller number of carefully selected indicators identified the same soil health trends amongst the investigated management systems, showing that a small set of indicators can indeed give adequate information for land management decisions. Andrews et al. (2002) found the same trend when comparing soil quality index methods for vegetable production systems in Northern California.

Scorecards for on-the-spot assessment in the field are prevalent amongst farmer-focused methods. This includes visual soil assessments (see Bünemann et al., 2018) and Soil Health Cards requiring little (or no) specialist equipment and focusing on immediate in-field assessment. Such Soil Health Cards have been developed in various contexts, including in India (Purakayastha et al., 2019), and for some states in the U.S.A (NRCS, n.d.*b*). By focusing on observable indicators, these approaches are often relying on physical soil properties, with chemical and biological properties implicit or missing. They are mostly subjective, but tend to broad ‘good, acceptable, poor’ conclusions rather than a quantified SHA.

The Agriculture and Horticulture Development Board (AHDB) recently developed an assessment calibrated for England and Scotland where each of 12 indicators is given a Red- Amber- Green (RAG) rating (Griffiths et al., 2018). Whilst there is no quantification of these ratings into a single score, the ratings are transparent, methods of measurement are clearly specified, and links are provided to government documents and databases. However, as above, 12 indicators including some requiring laboratory work is not feasible for extension across geographies.

Head et al. (2020) reviewed citizen science methods for assessing five soil health indicators: soil structure, organic carbon, biodiversity, nutrients and vegetation cover. Three of 32 measurement methods were classed as feasible in terms of time, cost and with suitable reliability- assessing biological activity, physical structure and vegetation cover. The reliability of twelve potential methods is not backed by peer-reviewed research (Head et al., 2020).

Existing farmer-centric SHAs meet the requirements specified above (Table 1), particularly in terms of farmer feasibility and decision support. However, they are locally designed, verified and implemented, with little flexibility for wider application. Statistical analyses (Lima et al., 2013; Tesfahunegn et al., 2011) demonstrate the value of including farmers in the SHA design process; their perspectives on soil health are often accurate (Guo, 2021; Head et al., 2020) and a valuable resource to support SHA.

5. Discussion: where next for global, farmer-friendly SHA?

SHAs have been proposed in scientific studies, by governmental entities, commercial organisations and farmer-led groups, with an associated range of priorities. Our brief review summarises examples of these and highlights relevant conclusions from other recent reviews and meta-analyses. Most existing SHAs satisfy some of our criteria, but this review did not identify a SHA that achieves all our requirements (Table 2).

There has been a rapid rise in discourse and scientific research on agriculture impacts on soil health and the importance of soil health to support regenerative approaches to land management, though the term 'soil health' is not consistently used or defined. However, this has not yet resulted in consensus on a practical SHA framework for farmers across geographical and production contexts and tends not to utilise local knowledge to its full potential (Hermans et al., 2021; Wade et al., 2022). Scientific studies use a huge range of indicators to describe soil health, with technology and soil science providing opportunities to develop new indicators and approaches (Wood and Blankinship, 2022). Amongst the growing list, it is possible to identify a shortlist that are most valuable to SHA; NAPESHM has proposed a top tier of 19 indicators, which was shortened to three by SHI (SHI, 2022). Further, SOC has been specifically identified as the single most important measurable indicator of soil health (Shukla et al., 2006) and is also commonly used (Figure 1). The effects of SOC on the soil combine direct and indirect effects across soil properties and are highly variable between soil types, climate, and initial conditions, though SOM might be a more accessible and closely related alternative (see Box), as it is directly related to meaningful management options and considers more than just C. Nevertheless, MDS proposed in scientific studies are ambitious in terms of data burden, with relevance to farmer decision-making low on the list of priorities and a particular reliance on lab facilities. Where farmers have been involved in development of MDS, the results are much more compatible with our feasibility and explanatory requirements but tend to have a local focus.

When assessing existing SHAs, our primary focus is feasibility for farmers, but the interpretability of SHA outputs is also critical for good soil management (Wade et al., 2022). Soil functions (as phrased in Table 1) are not necessarily intuitively linked to desired farmer outcomes, or to land management practices. For example, healthy soil helps with yield stability and resilience, but the links between indicator, assessment and yield impacts need to be understood and, ideally, quantified for SHA to provide effective decision support (Wade et al., 2022; Wood and Blankinship, 2022).

Across our categories of SHA, we find methods developed in specific geographies. Given the relative nature of soil health and substantial variation in natural soils and ecosystems, the threshold values for individual indicators in these SHAs vary (Figure 2), as do the interdependencies. Local threshold values would need to be established to allow application of these SHAs in new geographies.

In efforts to overcome the general complexity of scientific outputs, several top-down approaches exist where the user provides data and/or soil samples and a SHA is performed behind the scenes. Whilst geographical extension of these methods is possible- given the resources to do so- they are likely to remain prohibitively expensive for many and unlikely to adequately account for local context.

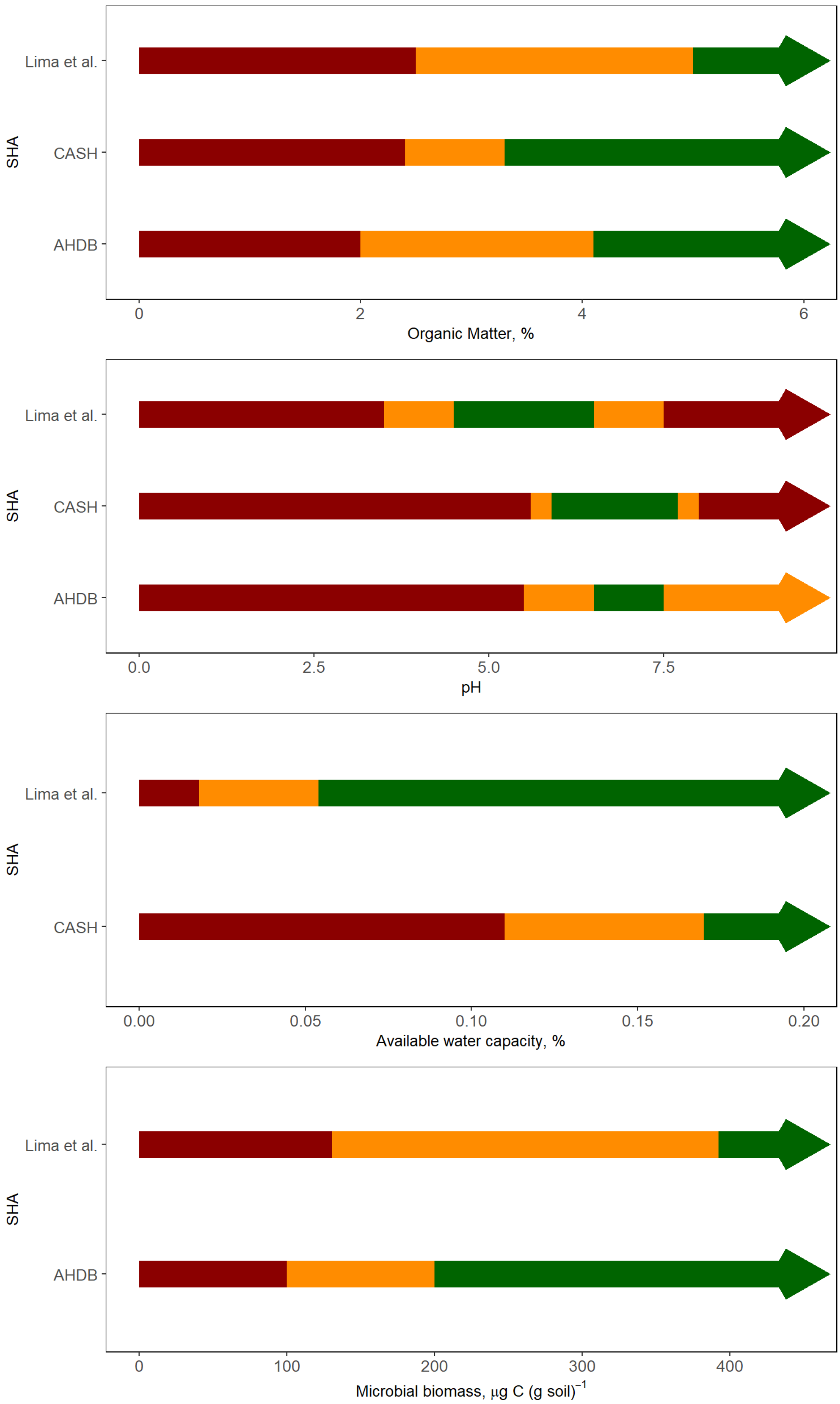

Figure 2 *Soil health indicator thresholds based on ~~from~~ CASH (Cornell Soil Health Laboratory, 2017~~6~~, for the USA), AHDB (Griffiths et al., 2018, for the UK) and Lima (Lima et al., 2013, for Brazil) SHAs. Soil*

organic matter, a~~A~~vailable water capacity, soil pH and~~,~~ microbial biomass ~~and soil organic matter~~ are shown. Green: good soil health, Amber: acceptable soil health, Red: poor soil health. Note: x~~y~~-axis is non-exhaustive: values above ~~those shown~~the range shown have the same categorisation as the maximum ~~y~~ value shown. As discussed in the text, these SHAs have different bases and approaches for defining agroecological parameters (e.g. soil texture classes) and also for transforming measured indicators into SHA. We have reconciled the different approaches in the three cited SHAs as follows. The AHDB approach gives the stated Red- Amber- Green thresholds, and does not apply a score to different indicator measurements. The CASH approach uses scoring curves between 0-100; based on their colour-coding, we have categorised a score ≤20 as Red, a score between 21 and 60 as Amber, and a score ≥61 as Green. The Lima et al. SHA uses scoring curves between 0-1; we apply limits comparable to CASH (i.e. 0-0.2, 0.21-0.6 and 0.61-1.0), using published data to estimate these values. Values shown are for a medium texture soil, which AHDB defines as 18-35% clay (Griffiths et al., 2018) and CASH defines as loam, silt loam, silt or sandy clay loam (Cornell Soil Health Laboratory, 2017). The values from Lima et al. (2013) are for 20-40% clay. Where further categorised by precipitation, the AHDB values are for medium rainfall (650-800mm). ~~Thresholds for 'good'/'bad' identified by cited SHAs. Note: y-axis is non-exhaustive: values above those shown have the same categorisation as the maximum y value shown. Values are for a medium soil. AHDB values are for sites with medium rainfall.~~

The process of establishing a global SHA includes establishment of a MDS, an indicator measurement protocol and an indexing approach with applicable threshold values for good/bad soil health. We perceive the following gaps that future work could seek to address. They are all to be undertaken across global farming contexts and include farmers in the process wherever possible. In fact, the most valuable efforts are likely to be cross-industry collaboration between scientists, farmers and advisory services, with support to access networks and knowledge from supply chain actors and policymakers. Of most value would be studies specifically addressing multi-regional evidence. Whilst single locality studies are of value, many such studies with a consistent inter-study approach are necessary to build an ensemble map of such evidence. Armed with this information, it would be possible to define a standardised and comparable SHA, with local context specificity as a major asset for decision support.

5.1. Quantitative analysis of individual indicator value to SHA

The concept of sufficiency (rather than completeness) is key to development of a globally viable SHA. The Pareto Principle (originating from Pareto, 1964) suggests that if, for example, 20 parameters comprehensively describe soil properties, four or five parameters may provide a description that is 80% as comprehensive. On average, scientific studies suggest that 11 indicators are needed in a MDS, though statistical data reduction techniques have been applied (Bünemann et al., 2018) and Lima et al. (2013) quantitatively validated a MDS of four indicators selected by farmers. Shukla et al. (2006) found SOC to be the most dominant soil quality indicator and measuring it would have additional benefits if the farmer were to consider carbon credits. Further, quantitative scientific research tends to overlook highly practical and farmer-favoured indicators such as Visual Evaluation of Soil Structure (VESS, Guimarães et al., 2011), visual plant inspection (e.g. Saha et al., 2022) and earthworm counting. Moncada et al. (2014) identified visual soil assessment as a valuable tool in determining threshold values.

Empirical evidence demonstrating the value of each additional soil health indicator to the conclusions drawn would help to identify priority indicators and sufficient MDS. The links between SH indicators and farm outcomes must also be evidenced and articulated. Considering farmer views on practical relevance and ensuring inclusion of the most practical (free, instant) indicators available would ensure progress towards a SHA ready to support management decisions.

Indicator tiers have been proposed by NAPESHM based on evidence strength; the proposed work could identify tiers of indicators by explanatory power. Such multi-regional statistical analysis is hoped to enable further discussion of how environmental contexts affect the relevance of individual indicators, and potential development of regional MDS options that could be considered comparable due to proven explanatory power. From these locally applicable options, farmers could select an MDS that is feasible for them; for example, given the different costs for specific indicator measurements, low-income farmers may use an MDS with relatively more visual and physical indicators than higher income farmers who have a larger choice of feasible, suitable indicators.

Further to local threshold values for indicators, environmental context may drive prioritisation of particular soil functions above others (SHI, 2022); for example, in water stressed (or water-logged) areas, the ability of the soil to regulate water is paramount to ecosystem health. As such, the local relevance and value of a SHA could be enhanced by recognising this and weighting indicators accordingly for local prioritisation. Doing so systematically and transparently could preserve comparability of assessments.

5.2. Measurement and sampling standardisation and cost-benefit analysis

Measurement and sampling requirements are a significant factor in both the viability and the effectiveness of SHA. Further, repeatability and reproducibility of indicator measurements are common priorities (Bünemann et al., 2018). SHA methods must be precise enough to identify material soil health changes driven by management. Sampling requirements must be production system agnostic and suitable for both large- and small-scale farming operations.

Soil indicator measurement and sampling methods vary significantly between studies and SHAs, which is confusing for users and complicates the collation of thresholds and baselines between geographies. Whilst this is known, and some work to standardise is underway (Stewart et al., 2018), it is also true that reported indicator results can vary significantly between laboratories (e.g., Wade et al., 2018). Laboratory variation suggests that any assumption of higher confidence in quantitative soil analysis by scientists compared to direct user data collection should be questioned. Taking account of local uncertainty in these values may make them less useful in discerning differences between local practices and, combined with relative high cost, less likely to be included in parsimonious, globally applicable SHA.

5.3. Development of soil health indicator thresholds

Throughout this paper, we emphasise the importance of environmental and production contexts for meaningful SHA. Baseline conditions specific to these contexts determine rating gradients and/or thresholds required for SHA. Developing global coverage of localised baselines and thresholds is demanding, therefore attention should be given to what factors determine the resolution required (e.g., soil texture, precipitation, ecosystem) and how they interact. Moncada et al. (2014) use decision trees, such that contextual descriptors and indicators appear alongside each other.

Firstly, existing SHAs and MDS represent an important base from which future work could develop. As far as we found, no single SHA has been calibrated for a global range of farming contexts. SMAF has been tested in South Africa (Gura and Mnkeni, 2019) and Brazil (Cherubin et al., 2017) and scoring curves for CASH have been developed for contexts outside the USA (e.g. Congreves et al., 2015; Rekik et al., 2018). Testing and calibration of existing SHAs in new environments would add to a database of threshold values, as well as progress the discourse on their global applicability.

There is already considerable evidence to support the establishment of potential values for some soil indicators. Recent work by Jian et al. (2020) generated the Soil Health Database (SHDB), with over 5,800 records of recorded soil information. With supplementary data collection, potential values and thresholds for soil health could be developed systematically. Farmer networks could be established to monitor indicators in areas with low data coverage and harness the crucial local knowledge of farmers. Multi-regional work on thresholds is likely to feed back into the relevance and importance of different soil health indicators.

6. Conclusions

To both support food security and prevent further environmental degradation, there is a need for a globally relevant and farmer-friendly SHA that has potential to offer practical indications of how soil health might be maintained or improved. Existing comprehensive approaches are impractical and expensive, while more farmer-focused, practical approaches are less easily transferred between environmental contexts.

Recently, there has been massive growth in attention to soil health testing across practitioners, researchers and industry and a wide range of tools and approaches are variously in use. To establish a globally applicable approach, further investigation is required. It has been well discussed that indicator thresholds for healthy soil vary between environmental and climatic contexts (Figure 2); future work could seek to establish meaningful indicator thresholds for SHA across contexts. For the goal of farmer practicality, it is also important to assess which indicators add information to a SHA in a given local context, since this would enable reduction of the MDS and associated data burden. SOC and SOM are both highly valuable in a SHA, and could be supported (and/or proxied) with observable traits and earthworm counts, which are low/no cost. Finally, further work should be done to understand the reliability and accuracy of different measurement and sampling protocols.

For greatest impact, our proposed foci for future work should be taken forward in a cross-industry collaborative approach between researchers, businesses, policy makers, and, above all, farmers. By building on the strong foundation of existing work and with a clear vision of farmer feasible SHA, consistent work could be undertaken by groups in different geographies and collated to build a global framework supporting and protecting soils and ecosystems.

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