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Review

The Role of Citizen Science in Meeting SDG Targets around Soil Health

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Abstract: Healthy soils are vital for sustainable development, yet consistent soil monitoring is scarce, and soils are poorly represented in United Nations Sustainable Development Goals targets and indicators. There is a clear need for specific ambitions on soil health, accompanying metrics, and cost-effective monitoring methodologies. In this paper, we review citizen science methods and platforms which could compliment structured soil monitoring programmes and contribute to filling this knowledge gap. We focussed on soil structure, organic carbon, biodiversity, nutrients, and vegetation cover. Each method was classified as red, amber, or green (RAG) in terms of time requirements, cost, and data reliability. Toolkits were assessed in terms of cost and requirement for specialist kit. We found 32 methods across the five indicators. Three soil monitoring methods scored green on all criteria, and 20 (63%) scored green on two criteria. We found 13 toolkits appropriate for citizen science monitoring of soil health. Three of them are free, easy to use, and do not require specialist equipment. Our review revealed multiple citizen science methods and toolkits for each of the five soil health indicators. This should pave the way towards a cost-effective, joined-up approach on soil health, informing national and international policy and supporting the move towards farmer-led, data-driven decision-making.

Keywords: soil health; citizen science; sustainable development goals; participatory monitoring; soil monitoring

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1. Introduction

Soil is vital to life on earth, and provides a vast range of ecosystem services. Soils provide the nutrients and physical structures that sustain plant growth and biodiversity; act as a buffer against pollution and soil erosion; absorb, release, and purify the water we drink; and regulate flooding [1–5]. Moreover, soils and the vast carbon sink they represent are critical in tackling climate change [6,7]. Although there is uncertainty around global soil organic carbon (SOC) estimates, soils and surface litter contain at least two to three times as much carbon as is stored in vegetation and the atmosphere [8].

The state of a soil is generally referred to in terms of its “quality” or “health” [9]. Many authors consider that there is no difference between the two and that the terms can be used interchangeably (e.g., [10]), while others argue that soil “health” tends to focus more on biotic components (i.e., soil fauna and microbes) and that the two concepts are quite distinct (e.g., [11]). However, other researchers argue that any quantitative assessment of soil quality or health should focus on the function that soils are expected to fulfil (e.g., [12]). Irrespective of terminology, soil health or quality is increasingly recognised as a strong underlying concept akin to other descriptors of soil biological, physical, and chemical properties. In this paper, we define "soil health" as "the continued capacity of soils to function as a vital living ecosystem that sustains plants, animals and humans" [13].

Poor management of soil health will contribute to reduced food security [14,15], greater flood risk [16], and increased greenhouse gas emissions [17]; representing a major risk to public health [18]. Yet, despite their vital importance and the range of ecosystem services they support, soils are under threat [5,19]. There is now clear evidence that human pressures on soil resources are reaching critical limits—approximately 33% of soils are degraded [4], and 24 billion tons of fertile soil are lost annually from agricultural systems worldwide [15].

Although soils are essential to sustainable development, to date they have never been the specific focus of a multilateral environmental agreement [18]. The UN conventions on Climate Change, Biodiversity and Desertification (United Nations Framework Convention on Climate Change (UNFCC); Convention on Biological Diversity (CBD); and United Nations Convention to Combat Desertification (UNCCD), respectively) embed soil health improvement as a cross-cutting theme, but do not explicitly discuss the crucial role of soils in the discourse and across different ecosystems. However, both the Land Use, Land Use Change and Forestry (LULUCF) inventory of the UNFCCC and the "4 per 1000" initiative do explicitly recognise the role of soil as a significant carbon sink [20]. Similarly, soil is poorly represented in the targets and indicators for the United Nations Sustainable Development Goals (UNSDGs) [21]. Not one of the 17 UNSDGs focus on soils specifically (although SDG 15 mentions land degradation and target 15.3 includes a specific soil indicator). While some argue that the critical importance of soil health in achieving the SDG objectives by 2030 has been exaggerated by soil scientists [10], others state that the absence of soil indicators reflects a lack of awareness of their importance in meeting SDG targets [22]. That notwithstanding, most agree that all SDGs have at least some type of dependence on soils and their functions [10,19]. Most notable for their relevance to soils are SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 6 (Clean water and sanitation), SDG 11 (Sustainable cities and communities), SDG 12 (Responsible consumption and production), SDG 13 (Climate action), SDG 14 (Life below water), and SDG 15 (Life on land) [18,22]. It has also been posited that soil may even have a role to play with respect to gender issues as in some countries soil preparation work is carried out almost exclusively by women, although cautions that many primary causes of issues highlighted by the UNSDGs are primarily political and economic in nature [10].

Continued soil degradation will slow or prevent the meeting of SDG targets that are underpinned by soil. This ongoing degradation is associated with a significant lack of specific ambitions and legislation around soil health at global and continental levels, alongside a lack of standardised metrics, challenges in assessing soils over large areas, and a disconnect between soil governance and the land policies upon which it depends [23–27]. A variety of monitoring frameworks and guidelines do exist, such as the IPCC Guidelines for Greenhouse Gas Inventories [28] which include methodologies for tracking the change in soil carbon, the Land Degradation Neutrality (LDN) target [29], the World Soil Charter [30], the Voluntary Guidelines for Sustainable Soil Management [31], and the "4 per 1000" initiative [20]. However, to date, none of these provide the unified approach to data collection and interpretation that is required to calibrate soil health indicators in the round in a reliable manner across countries (but see [32] on LDN). Moreover, divergence in methodological approaches among the research community further hampers efforts to generate baseline data against which progress could be measured, and there remains ongoing disagreement around the most effective way to measure carbon in soils [33,34] and carbon emissions [8]. That being said, there is general agreement about changes that indicate a degradation in soil health over time if methods in a location are consistent. These include a decline in soil organic carbon and increased compaction, contaminant levels, and erosion, among others [23,25,27].

A similar lack of attention for soils is observed in statutory monitoring. While soil, water, and air are all essential to human life and society, soil is often the forgotten and neglected component compared to other environmental metrics in monitoring efforts (e.g., [35,36]). For example in Europe, while EU directives have been established for air [37], water [38], and biodiversity [39], the European Soil Framework Directive was withdrawn in 2007 and is yet to be re-tabled, although the EU Soil Thematic Strategy goes some way to addressing soil health and quality at the EU level [40], and will be updated in 2021 as part of the EU Biodiversity Strategy for 2030 [41]. Ronchi [36] highlights the lack of coherence in the legislative framework, policy instruments, coordination, and monitoring among member states which has resulted. Financial and human resource constraints also limit the collection of soil data at scale using traditional approaches, particularly in developing countries where the funding required creates a significant barrier [42], leading to infrequent sampling and patchy coverage. In industrialised nations, the issue is more about lack of funding for soil monitoring relative to that available for other natural assets (again driven by lack of political targets and strategies focussed on soil [36]) rather than because soils are intrinsically more diverse, stable, or dynamic than other assets and thus harder or more costly to measure compared to air, water, or biodiversity.

As of July 2019, 26% of the environment-related SDG indicators still have no established methodology (i.e., Tier III), while a further 32% have insufficient data available for global tracking [43,44]. The lack of specific measurable indicators and targets have been identified as a specific reason for the failure of meeting global biodiversity targets [45]. There is therefore a clear and important need for specific ambitions and accompanying metrics to fill existing knowledge gaps around soil if soil health is to be improved. Traditional data sources for soil health such as national monitoring programmes involving soil sampling and analysis are underfunded and to date insufficient in coverage, whilst new and non-traditional data techniques such as remote-sensing and citizen science sources can help accelerate measurement of global progress against the SDGs [46,47].

Citizen science, defined here as "intentional collaborations in which members of the public engage in the process of research to generate new science-based knowledge" [48], is an example of an emerging non-traditional data source that could meet the shortfall in monitoring by providing the soil health data needed [49]. In order to provide useful data, citizen science approaches to soil monitoring and management relevant to the SDGs must be standardised and applicable on a wide scale and will require significant public engagement. Given that agricultural soils represent 50% of the globe's habitable land surface [50], farmers and land managers are an essential group with which to engage at an early stage; as the gatekeepers of these soils, farmers have the opportunity and motivation to protect soils. To be effective, farmers require methods that are relevant (to farming operations as well as broader considerations of soil health), appropriate, reliable, and inexpensive, and to date little research has reviewed the extensiveness of existing citizen science soil monitoring methods or platforms that could be appropriate.

Where formal/traditional soil sampling is practiced by farmers (primarily in high-income sectors in high-income countries), some consider the requisite laboratory tests to be costly, complex, infrequently conducted, and lacking standardisation [51,52]. There can also be a significant delay in obtaining results, negating their utility in farmer decision-making with respect to, e.g., fertiliser requirements [53]. There is also evidence that analysis requested from commercial laboratories by farmers prioritise short-term requirements such as fertilizer needs over longer-term metrics such as soil organic carbon and soil biological activity (e.g., [54]). These findings can be challenged or explored further, for example, whether costs really are excessive considering their potential value in helping to conserve the most valuable capital asset of a farmer—their soil. Moreover, there is nothing intrinsically more expensive about soil analysis relative to water and air analysis, but farmers are currently not asked to undertake them to demonstrate they are not impacting environmental quality downstream. Furthermore, farmer focus on nutrient levels for fertiliser needs is influenced by the dominance of fertiliser companies in farm management advice and soil testing, which results in poor understanding as to standards and actions that can be taken to remedy other soil health issues identified (e.g., loss of soil organic carbon or compaction).

In LEDC's, laboratories are scarce and soil testing prohibitively expensive for most small-scale farmers [55]. Alongside soil sampling, farmers possess a deep understanding and local knowledge of soils and continuously take informal soil observations, but these are neither standardised nor typically recorded [56,57]. There is therefore a clear and important role for citizen science in complimenting statutory monitoring and traditional approaches, and empowering farmers to effectively monitor global soils [58,59]. The data created could ultimately feed into national and international databases to enable a picture of soil health to be established at relevant scales and establish if we are meeting SDG targets. Such an approach would also enable us to harness the existing experience and deep understanding of soils that farmers possess that does not translate to laboratory soil testing. Citizen science monitoring of soil health will also support farmers in minimising their environmental impacts and enable them to understand impacts of changes in management practises through ongoing, objective monitoring. Furthermore, citizen science approaches can engage farmers in the importance of soil health through putting them in control of understanding their own soils, supporting the critical move towards farmer-led, data-driven decision-making.

Several papers have explored the general role of citizen science in monitoring and implementation of the SDGs [42,47,60–62]. The most recent and comprehensive of these reported that citizen science is already contributing to five Tier I, II, and III indicators through SDG targets 9.1 (resilient infrastructure—OpenStreetMap; Tier II); 14.1 (marine pollution—UN environment method; Litter Intelligence; Tier III); 15.1.2 and 15.4.1 (terrestrial, freshwater, and mountain biodiversity in protected areas—>10 methods; Tier I); and 15.5.1 (Red List Index—>10 methods; Tier I) [63]. Furthermore, the review identified where existing citizen science methods could contribute to a further 76 targets (45%) across all 17 SDGs.

To date, no review has specifically explored the role of citizen science soil health monitoring in meeting relevant SDGs, although targets 15.1.2 and 15.4.1 are considered relevant to soil health since they cover protected areas [64]. Furthermore, only two citizen science projects with soil health relevance (GROW and LANDMARK) are included in the above review [63]. This is likely a reflection of there being no SDG explicitly or primarily focused on soil health—despite it being embedded within other SDGs, it seems to have slipped through the cracks to become the invisible component.

The aim of this paper is to provide a review of existing citizen science methods and platforms for soil health monitoring which could be used to provide data for the SDG indicators relevant to soil health, thus meeting the deficit of other evaluations. It considers the cost, reliability, and accessibility of existing methods and toolkits, and provides recommendations on what is required to enable farmers to contribute effectively to the SDGs on soil health.

2. Materials and Methods

2.1. Defining Citizen Science Methods and Monitoring Parameters

As described in the introduction, our definition of citizen science is based on that of Shirk [49]. However, there are existing soil monitoring activities that do not explicitly use the term "citizen science" but that would fall under this definition and have the potential to contribute to SDG indicators. We therefore employed a broader classification that included "participatory monitoring" [65], "public participation" [66], and "community-based monitoring" [67].

There are a multitude of metrics by which soil health can be monitored, although not all are suitable for citizen science due to their complexity, nor do all provide robust data. We distinguished between soil monitoring methods (that focus on one parameter of soil health), and soil monitoring toolkits (that assess multiple metrics, and are typically part of a public facing project or platform). In order to ensure we selected the most relevant indicators of soil health from both political and environmental perspectives, we assessed existing frameworks and ambitions for soil health including the EU Mission Board Soil Health and Food [64], the Green Deal's Farm to Fork Strategy [68], the UNCCD, and the

SDGs. From these, we identified 5 key soil health indicators: soil structure, soil organic carbon, soil biodiversity, vegetation cover, and soil nutrients (Table 1).

Table 1. Definition, role of, and interdependencies between key indicators of soil health. Numbers in the "Interdependencies" column refer to Figure 1.

Parameter	Definition	Role in Soil Health	Interdependencies
Soil structure	The aggregation of soil particles (sand, clay, silt, organic matter, and nutrients) into porous compounds. Soil structure also refers to the arrangement of these aggregates, separated by cracks and pores.	Soil structure determines how fast water, air, and gas enter and move through the soil, which in turn influences soil resource availability for plants and habitat for other organisms, including micro-fauna, microbes, and fungi.	(1) Well-aggregated soil enhances aeration. (2) Well-aggregated soils allow water to pass through the soil structure. (3) Soil aggregates are strongly bound to one another and are therefore more resistant to erosion.
Soil organic carbon (SOC)	The fraction of carbon in soils formed from organic matter. SOC is a balance between the input of organic matter (plant and animal residues) and its removal by harvesting, erosion, leaching, and microbial decomposition.	Typically, increasing SOC both reduces atmospheric greenhouse gases and positively influences a plethora of soil health parameters, which, in turn, increases productivity on short and long timescales and improves resilience to climate-related risks (but see [69]). SOC improves resistance to soil erosion, water-holding capacity, soil fertility for plants, and soil biodiversity.	(4) Organic matter provides exchange sites onto which dissolved nutrients can adsorb. (5) Organic matter buffers changes in pH, which maintains an optimal/appropriate pH for nutrient availability for the crops or wildlife present. (6) Organic matter typically buffers pH, which reduces the mobility of harmful heavy metals (except where pH is very low). (7) Organic matter provides a source of nutrients, which fuels biological activity.
Soil biodiversity	All forms of life that live within the soil layer, ranging from soil microbes (including bacteria and fungi) to meso-fauna (e.g., Collembola) and macro-fauna (e.g., earthworms).	Soil biodiversity and biological activity provides many important ecosystem functions including supplying nutrients, disease and pest suppression, aeration, and bioremediation. High levels of soil biodiversity are an important control of overall soil health and function.	(8) Microbes decompose organic pollutants and convert them to non-toxic molecules (bioremediation). (9) Soil animal and microbes decompose organic matter and transform it into nutrients, aiding plant growth. (10) Microbes help to suppress disease and pests through predation and competition. (11) Microbes secrete glues that bind soil particles together and increase soil stability. (12) Soil faunae break down organic matter and vertical movement spreads nutrients between soil layers. (13) Soil faunae create channels, nests, and galleries, which aid infiltration. (14) Mixing and burrowing by soil faunae increases aeration.

Table 1. *Cont.*

Parameter	Definition	Role in Soil Health	Interdependencies
Vegetation cover	The area of foliage on or near the soil surface, composed of contact cover (foliage in contact with the soil, including prostrate stems, leaves, litter, and basal areas of plants) and canopy cover (standing plant herbage greater than 5 cm in height).	Soils with higher vegetation cover generally perform better agriculturally than those that remain bare for a large portion of the year, as vegetation cover provides a variety of benefits to soil health, including organic matter supply, improved structure and porosity, and energy, which promotes microbial activity.	(15) Vegetation cover supplies organic matter to soils. (16) In exchange for nutrients, plants provide energy and habitats for rhizobacteria and fungal symbionts in soils. (17) Root networks improve soil structure and porosity by disrupting the soil. (18) Root networks stabilise the soil and reduce runoff. (19) Root networks enhance the downwards flow of water. (20) Vegetation cover provides habitats for macrofauna. (21) Root networks disrupt soil, and aid porosity and aeration. (22) Vegetation cover reduces rainfall velocity and soil splashing, preventing erosion. (23) A plant may have high biomass but not provide much ground cover (e.g., maize crops).
Soil nutrients	Soil macronutrients are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulphur, magnesium, and calcium. Micronutrients are molybdenum, copper, zinc, manganese, iron, nickel, boron, cobalt, sodium, silicon, and chlorine.	Soil nutrients are vital for life to exist in the soil and above. It is important that appropriate nutrient levels are maintained for the function of the soil, e.g., production or conservation, and limit the environmental impact that can occur when they leave the soil.	(24) Nutrient retention increases nutrient supply for optimum plant growth. However, nutrients appropriate for crop growth will be too high for many nature areas within a farm.

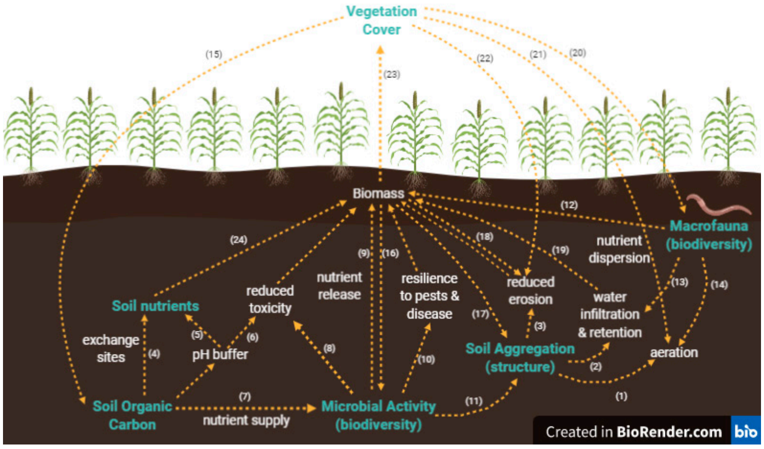

Figure 1. Interdependencies of soil health metrics.

Inclusion in the review required that each soil monitoring method or toolkit met the following criteria:

- can be carried out by a non-expert with no or minimal training (i.e., simple training manual);
- does not require specialised/costly equipment (over GBP 50/USD 67/EUR 56);
- can be carried out within a particular timeframe (2 h, excluding processing times);
- provides reliable data (as evidenced by peer-review assessment) that measure change and are comparative with traditional approaches (with the exception of methods in widespread use in toolkits despite lack of validation);
- for standalone methods—shows interdependencies and positive feedback mechanisms that interlink it with other metrics to provide a comprehensive picture of soil health (see Figure 1).

Methods were excluded if they were still in the process of development and therefore had little information on costs, time commitments, and reliabilities; or if studies determining their reliability were of poor quality.

2.2. Identifying Citizen Science Projects

Relevant citizen science methods and toolkits for monitoring soil health across the five soil health indicators were collated as part of micro-internships within Earthwatch Europe's Sustainable Agriculture team [70] by a group of 5 interns in June 2020. For each of the 5 metrics, we used Boolean operators to identify relevant methods and toolkits appropriate for the general public using the search term of the metric plus "citizen science", or "participatory", or "monitoring", or "community-based monitoring". An array of search engines including Solo, Web of Science, ScienceDirect, Google Scholar, and Wiley Online Library were used to research methods of assessing that metric appropriate for the general public. Grey literature was also used where appropriate—for example, in searching for existing toolkits. Searches also covered citizen science-specific web pages, including the inventory of citizen science projects for environmental policies [62], SciStarter [71], and Zooniverse [72]. Finally, the interns used contributions from the co-authors on the basis of their extensive knowledge of soil-related citizen science initiatives and projects.

Each soil monitoring method was assessed and classified as either red, amber, or green (RAG) in terms of three principal parameters—(a) time and repetition requirements, (b) cost and required materials, and (c) strengths and limitations in terms of reliability/accuracy; with green being optimal and being red least favourable (Table 2). For soil biodiversity, a differentiation was made between soil biological activity and soil biodiversity, since there can be redundancy in soil biota such that only a few organisms can perform most functions and high activity does not reflect true biodiversity (i.e., a complex mix of appropriate taxa).

Soil monitoring toolkits were each assessed and classified as either red, amber, or green (RAG) in terms of two parameters—(a) cost to access instructions and (b) requirement for specialist kit and/or lab testing (Table 2). Which of the five soil health indicators could be measured was also assessed. Methods and toolkits that scored red on two or more parameters were included in the results table but excluded from analysis in terms of being considered an appropriate and reliable citizen science method.

3. Results

The literature review resulted in 33 citizen science soil monitoring methods across the five indicators of soil health (Table 3), but one method (Visual Evaluation of Soil Structure (VESS)) was excluded from further analysis due to scoring red for both time required and reliability. Of the remaining 32, only 3 soil monitoring methods scored green on all criteria in the RAG assessment (Teabag Index for assessing soil biodiversity, specifically soil biological activity; Infiltration Rate for assessing physical structure; and quadrat-based Visual Assessment for vegetation cover), but this increased to 20 (63%) when requiring only two RAG criteria to be green. Overall, 66% of methods met green criteria for cost, compared to 47% for time requirement and 38% in terms of reliability.

In terms of the five soil health indicators, there was variability in number of monitoring methods available and their average ranking against RAG criteria. In particular, there were limited methods for monitoring soil nutrients that were appropriate for citizen science and provided reliable results, and even those which met eligibility criteria for inclusion scored lower on the RAG assessment than the other four methods. Furthermore, for 38% (12) of the methods, the review did not find any peer-reviewed studies that assessed the reliability of the citizen science method in comparison to professional methods. For methods with available information on reliability, only one scored red while 50% scored green, indicating a high level of reliability. The greatest number of different citizen science methods available for each soil health indicator were found for soil carbon (10) and soil biodiversity (9). However, six of the nine soil biodiversity methods only provided a measure of soil biological activity rather than actual biodiversity, while 4 of the 10 soil carbon methods represented a proxy rather than an actual measurement.

Table 2. Detailed breakdown of red, amber, or green (RAG) assessment for time required, cost, and reliability of each soil monitoring method, as well as for cost and specialist kit requirement of toolkits. "Specialist" refers to items not available in standard hardware stores.

	Soil Monitoring Methods			**Soil Monitoring Toolkits**	
	Time	**Cost**	**Reliability**	**Cost**	**Specialist Kit**
Green (G)	Measurement does not require repetition more than once a year and takes less than 30 min, or needs to be taken multiple times a year but takes less than 15 min.	Farmers were likely to have all materials to hand; any additional outlays cost less than GBP 15, and no specialist equipment was required. "Free" was specified when the test required no equipment beyond a spade, smartphone, or laptop.	Studies show there is no significant difference between the method listed and lab/professional methods in terms of error and reliability of detecting change.	Free manual/guides.	No kit beyond items available at most hardware stores/already in most homes.
Amber (A)	Measurement does not need to be taken more than once a year and takes 30–60 min, or does need to be taken multiple times a year but takes less than 30 min.	An initial outlay of under GBP 20 was required, or there was a negligible cost per sample.	Studies show the results collected through the method listed show similar trends to professional/lab data.	Free manual/guides but subscription may confer an additional cost.	≤2 pieces of specialist kit and/or laboratory analysis.
Red (R)	Measurement does not need to be taken more than once a year but takes more than 60 min, or needs to be taken multiple times a year and takes less than 60 min.	An initial outlay of more than GBP 20 is required, or costs for each sample taken are more than GBP 5. Exact costs are provided where available in Table S1.	There is poor agreement between the method listed and lab/professional methods, or its ability to detect small-scale change.	Manual/guides are not open access.	>2 pieces of specialist kit and laboratory analysis.

In terms of existing platforms, the review revealed there are 13 toolkits that could be considered appropriate for citizen science monitoring of soil health, while 4 toolkits were excluded due to scoring red for both cost and specialist kit/laboratory analysis requirement (Table 4). Only five of the platforms were completely free to use, and of those, two required significant amounts of additional equipment that conferred additional costs. Furthermore, five toolkits were part of ongoing or completed research projects and not open to public use. A total of 85% of the toolkits assessed three or more of the five key soil health indicators, 69% assessed at least four indicators, and 23% assessed all five indicators (according to the information publicly available). Eleven of the toolkits were either aimed explicitly at farmers or included farmers as a sub-set of wider public participation approaches to soil monitoring, while two were aimed at soil sampling in gardens and public places.

Table 3. Overview of methods used to measure each of the five soil health indicators (structure, organic carbon, biodiversity, vegetation cover, and nutrients).

Metric Type	Test Name	Kit Required	Time	Cost	Reliability
Soil physical structure	Bulk density	Sturdy ring, hammer, weighing scale or kitchen scale, metal rod, market, paper cups, sealable bags, and access to microwave or oven	(A)	(A)	N/A
	Drop shatter test	Plastic bag and spade	(G)	(G)	N/A
	Infiltration rate	PVC/metal pipe, marker, ruler/tape measure, sharpening file, saw, water bottle, measure jug	(G)	(G)	(G) [73]
	Slake (wet aggregate stability)	Two glass jars, wire mesh, wire cutter, spade, and timer	(A)	(G)	(G) [52]
	Spading ease	Spade	(G)	(G)	N/A
	Visual Evaluation of Soil Structure (VESS)	Spade, tape measure, and tray	(R)	(G)	(R) [74,75]
	Active carbon test	0.1 M $CaCl_2$ solution, digital scale, brush, colour chart, water, 30 mL standing tube, plastic squeeze bulk pipette, $KMnO_4$ solution, measuring spoons, tray, timer	(G)	(A)	(G) [76]
	Loss on ignition field test	Spade, metal tray, digital scale, fan oven, sieve, spoon, bowl, empty tin, tongs, camping stove	(R)	(G)	N/A
	MO DIRT active carbon test	Digital scale, brush, colour chart, water, 30 mL standing tube, plastic squeeze bulk pipette, $KMnO_4$ solution, measuring spoons, tray, timer	(G)	(A)	(G) [76]
	Nutrients (proxy)	Example using the Rapitest soil test kit: brush, water, plastic squeeze bulk pipette, plastic container (1 L), measuring cups, timer	(A)	(A)	N/A
	SOCit	Free app (iPhone), spade, colour chart	(G)	(G)	(A) [77]
	Soil colour protocol	Auger, soil colour chart, plastic squeeze bulb pipette, mallet	(G)	(G)	(A) [78,79]

Table 3. *Cont.*

Metric Type	Test Name	Kit Required	Time	Cost	Reliability
Soil organic carbon	Soil texture (proxy)	Auger, brush, water, plastic squeeze bulk pipette, mallet, diagram, stick, knife	(A)	(G)	N/A
	Solvita Soil Respiration Test (proxy)	Solvita test kit, digital scale, brush, water, plastic squeeze pipette, sealable bag, tray, timer	(A)	(R)	N/A
	USDA active carbon test	Spade, $KMnO_4$ reagent, field colour chart, field spectrophotometer	(G)	(R)	(G) [76]
	USDA Soil Respiration Test (proxy)	Sturdy ring, lid with rubber stoppers, wooden block, mallet, soil thermometer, 2x plastic tubing, 2 needles, Draeger tubes, syringe, timer	(R)	(G)	N/A
Soil biodiversity	Bait lamina strips *	Bait lamina strips; markers, e.g., tent pegs, plant labels	(G)	(A)	(G) [80,81]
	Cotton strip assay using imagery *,(i)	Cotton strips, scanning software (not yet publicly available, Nachimuthu et al. (2007))	(G)	(G)	(A) [82]
	Earthworm watch	Plastic bottles, mustard powder, vinegar, trowel, trays/pots	(A)	(G)	(G) [83,84]
	OPAL Soil and Earthworm Survey	pH strips, mustard powder, vinegar, ruler, trowel, plastic bottle, bin bags, tray	(A)	(G)	(G) [83,84]
	Pitfall traps (effective for ground-based taxa)	Glass jars, spade, tape measure, weighing scales, sieve, markers	(R)	(A)	(A) [85,86]
	Soil Your Undies *	Cotton underwear	(G)	(G)	N/A
	Solvita Soil Respiration Test *	Solvita test kit, digital scale, brush, water, plastic squeeze pipette, sealable bag, tray, timer	(A)	(R)	N/A
	Teabag Index *	Teabags; trowel; markers, e.g., tent pegs, plant labels	(G)	(G)	(G) [87,88]
	USDA Soil Respiration Test *	Sturdy ring, lid with rubber stoppers, wooden block, mallet, soil thermometer, 2x plastic tubing, 2 needles, Draeger tubes, 140 mL syringe, timer	(R)	(G)	N/A

Table 3. *Cont.*

Metric Type	Test Name	Kit Required	Time	Cost	Reliability
Soil vegetation cover	Canopeo app	Smartphone	(A)	(G)	(G) [89–92]
	Remote sensing (ii)	Laptop/desktop	(R)	(G)	(G) [93–95]
	Visual estimation	Nail, string/tape, boot	(G)	(G)	(A) [96–100]
	Visual estimation	Quadrat	(G)	(G)	(G) [96–100]
Soil nutrients	Colourimetric strips	Differs depending on brand; typically all supplies available in a kit	(A)	(A)	N/A
	Colourimetric solution tests (iii)	Differs depending on brand; typically all supplies available in a kit	(A)	(A)	(A) [101–103]
	Colourimetric solution tests with Akvo Caddisfly app	Colourimetric test strips; smartphone	(A)	(G)	(A) [104,105]
	Weed and plant monitoring	None	(G)	(G)	(R) [106]

* refers to methods that measure soil biological activity rather than true biodiversity. "N/A" is used when no studies were found exploring the reliability/accuracy of the citizen science method in comparison to professional methods. Blue background color Indicates metrics removed from further analysis due to low RAG score. (R) = red; (A) = amber; (G) = green. Table S1 provides details on footnotes (i), (ii), and (iii); specific information on time commitment and costs; and weblinks to each method presented.

Table 4. Overview of citizen science soil monitoring toolkits available to assess two or more indicators of the five indicators of soil health as defined in the Materials and Methods section (Str = soil structure, Bio = soil biodiversity, Car = soil organic carbon, Nut = soil nutrients, and Veg = vegetation cover). "N/A" is used when information on cost and equipment required was not freely available. Table S2 provides weblinks to each toolkit and an overview of target audience, accessibility, and geographic scope.

Toolkit Name	Str	Bio	Car	Nut	Veg	Run by	Cost for User	Specialist Kit/Lab Analysis Required
SoilMentor	x	x			x	SectorMentor Vidacycle (https://soils.vidacycle.com/)	🟥	🟥
MO DIRT Soil Health Survey	x	x	x	x		Missouri EPSCoR (https://modirt.missouriepscor.org/sites/default/files/files/Soil%20Health%20Survey%20Manual_Master_double%20sided%285%29.pdf)	🟩	🟥
Soil Quality Test Kit	x	x		x		Natural Resources Conservation Service Soils, USDA (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=nrcs142p2_053873)	🟥	🟥
Soil Health Test Bucket	x	x	x	x		Natural Resources Conservation Service Soils, USDA (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=nrcs142p2_053870)	🟥	🟥
Soils Cross-Cutting Project	x	x	x	x		Collaborative Crop Research Programme (https://www.ccrp.org/wp-content/uploads/2019/08/SoilToolKitManual_SV6.3_August2019.pdf)	🟥	🟥
Soil Health Extension Toolkit	x	x		x		Sugar Research Australia (https://sugarresearch.com.au/soilhealth/)	N/A	N/A
Soil Navigator DSS	x	x	x	x		LANDMARK (http://landmark2020.eu/pillars/soil-navigator-pillar1/)	🟧	🟧
SQAPP	x	x	x	x		Wageningen University (https://isqaper-is.eu/)	🟩	🟩
Cool Farm Tool	x	x	x	x	x	Cool Farm Alliance (https://coolfarmtool.org/)	🟧	🟧
Soil Health Scorecard	x	x	x	x		Agriculture and Horticulture Development Board (https://ahdb.org.uk/soil-health-scorecard)	🟧	🟧
Wisconsin Soil Health Scorecard	x	x	x	x	x	UW-Madison Centre for Integrated Agricultural Systems (https://www.cias.wisc.edu/wp-content/uploads/2008/07/soilhealth_screen.pdf)	🟧	🟧
Soil Structure Assessment Kit	x	x				Victorian Resources Online (http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/0d08cd6930912d1e4a2567d200257 71de891c76430335ca2576cb00031f $FILE/ATT4FY81/soil%20structure%20assessment%20kit%20-%20red%20duplex%20soils.pdf)	🟩	🟧
Yara Farmers Toolbox	x	x	x	x	x	Yara (https://www.yara.co.uk/crop-nutrition/farmers-toolbox/soil-testing-and-analysis/)	N/A	🟩
Earthworm Watch	x	x	x		x	Earthwatch Europe (https://www.earthwormwatch.org/)	🟩	🟩

Table 4. *Cont.*

Toolkit Name	**Str**	**Bio**	**Car**	**Nut**	**Veg**	**Run by**	**Cost for User**	**Specialist Kit/Lab Analysis Required**
OPAL Explore	x	x				Imperial College London (https://www.imperial.ac.uk/opal/surveys/soilsurvey/)	🟩	🟩
Atlas of Biological Work	x	x	x		x	Soil Carbon Coalition (https://atlasbiowork.com/)	🟧	🟧
The Soil Carbon project	x	x	x			The Farm Carbon Toolkit Community (https://farmcarbontoolkit.org.uk/soil-carbon-project)	N/A	N/A

4. Discussion

Soil is the link between the atmosphere, biosphere, hydrosphere, geosphere, and anthroposphere, and well-managed soils are critical to advancing many of the SDGs. Despite its importance, protecting and improving soil health has been under-represented in multilateral agreements focused on sustainability, including the SDGs. This oversight has contributed to a lack of standardised metrics for soil monitoring, limited approaches to collecting soil data at regional or national scales, and a resulting paucity of data on soil health globally. Meeting soil-related SDG targets by 2030 will therefore be extremely challenging without the use of complimentary approaches such as citizen science. Citizen science methods for soil monitoring could provide standardised, simple approaches that fill knowledge gaps and provide valuable, reliable information on progress towards global targets. There is a clear and important role for citizen science in enhancing statutory monitoring and empowering farmers to effectively monitor global soils, allowing farmers, policymakers, and researchers to access data that will enable effective decision making to protect and improve soil health.

That said, citizen science approaches cannot (and should not) replace statutory and traditional monitoring, and there is still a need for robust structured soil monitoring programmes alongside citizen science programmes to provide the unbiased and statistically robust framework on which other data can be integrated [54]. Developing thresholds and standards for different soil indicators is also an urgent need and should be considered no more challenging than is already available for other natural resources in many regions (e.g., the EU) for air, water, and biodiversity. It simply requires the political will, policy framework, and funding for the research. It should be emphasised that not all soils are on farms, and national programmes of forestry, urban, and conservation soils are also needed to provide a truly national picture of soil health.

Our review revealed there are a whole host of citizen science methods and toolkits that are (or have the potential to be) appropriate for monitoring different aspects of soil health. Multiple assessment methods have been developed for each of the five key soil health indicators identified in this study, although they vary in terms of ease of use, cost, and reliability. Encouragingly, more than half of the methods have already been assessed against traditional or laboratory-based approaches in terms of reliability. However, the absence of information on reliability of the remaining metrics is a limitation of our study, meaning we should be cautious about interpreting the results as we may have underestimated the true number of metrics that score green on two or more RAG criteria. Furthermore, while some of the metrics have already been assessed across different soil types and environments to ensure comparability in measuring progress against the SDGs (e.g., [76]), others are currently only appropriate for limited soil contexts (e.g., [77]) and require significant work to make them appropriate for global monitoring.

Our review confirmed that there are several soil health toolkits available that assess at least four of the five key indicators. Some of these are already being used to help characterize and map soil properties and health at large spatial scales, while the potential of others remains underutilised. As expected, farmers were the primary audience for the soil health toolkits, a positive sign that there is some recognition that farming communities are a priority target and can contribute significantly to soil data collection. However, despite these encouraging findings, some clear limitations of existing methods and toolkits emerged. Shortfalls of standalone methods include the finding that the majority of soil biodiversity metrics actually only measure degree of soil biological activity rather than the diversity of microbial organisms in soil, an important distinction for assessing soil health. In addition, our evaluation revealed that while cost was infrequently a limiting factor (with all five indicators having multiple tests available that scored green for cost), time requirements were more variable, with limited quick options available for robust assessment of soil nutrients and vegetation cover in particular. This is an important finding, since farmers are typically very time-poor and thus this could be a significant barrier to uptake. Furthermore, our review revealed that citizen science monitoring options are particularly limited for soil nutrients. There is clear need for further research to develop appropriate methods that are low cost and quick to implement.

Among the toolkits, the majority required access to equipment and/or laboratory analysis or sat behind a paywall. Furthermore, many were part of closed research projects that were either not publicly available or were no longer collecting data. Similarly, collected data were rarely available on opensource platforms that could be of use to wider stakeholders and contribute to national or global soil health monitoring. More broadly, uptake of citizen science methods among farmers could unintentionally skew findings (e.g., be biased towards farmers already highly engaged in soil health and associated management practices), which is problematic for providing a robust national metric, as is the fact that inter-observer reliability can be high in citizen science monitoring. These limitations add further support to the argument for wider soil monitoring programmes to be developed alongside citizen science.

Despite these limitations, our review highlights that appropriate and robust citizen science approaches do exist, and some are well established for monitoring soil health at large scales. Concurrently, the work of many soil scientists (e.g., [9,18,19,22]) confirms the importance of soil and soil protection in reaching the SDGs. What is therefore lacking is a joined-up approach that links these monitoring methods with soil health targets at national and global levels. Evidence of this disconnect is highlighted by the fact that none of the 16 toolkits identified mention the SDGs or other multilateral agreements relevant to soils (although the Soil Navigator Decision Support System (DSS) references the potential of the tool to complement the Farm Sustainability Tools for Nutrients included in the EU's Common Agricultural Policy 2021–2027 proposal).

These results also highlight that there is a clear need (and opportunity) to bring together existing robust, standalone citizen science methods for monitoring the five key indicators of soil health and to package them into a farmer-focused toolkit that is relevant, reliable, and inexpensive, and that does not require access to scientific equipment or laboratory testing. Development of online databases that allow data sharing in a format that respects farmers' privacy would enable the resulting data to feed into national and international databases, building a picture of soil health at relevant scales and establishing whether SDG targets are being met. Such an approach would also support farmers in minimising their environmental impacts, engage them in the importance of soil health, and put them in control of monitoring their own soils, supporting the move towards farmer-led, data-driven decision-making.

However, many farmers are hampered from taking positive action on soils, not only because they do not know if their soil is healthy, but because even with this knowledge, they do not know what steps to take to improve their soil [64]. Therefore, it is critical that any citizen science action must be part of a wider programme of improved access by farmers to independent advisory services that can provide support in benchmarking the resultant soil data on the basis of local soil type, land use, and climate combinations, and provide practical advice on what options are available to improve soil health.

5. Conclusions

In order to make global progress against SDG targets linked to soil health, especially SDG 15.3, we need agreement on standardised testing and reporting methods, and comparable effort and funds provided for the development of thresholds and standards for different soil indicators, as is available for monitoring air, water, and biodiversity. Progress is already being made in this area for laboratory testing;

for example, the Global Soil Laboratory Network [107] are working to develop harmonized standards for soil analytical data across soil laboratories. However, non-laboratory sampling also forms an important part of soil health monitoring, and here metrics must be simple to assess so that participation is not hampered for those in low-income countries with limited access to the requisite infrastructure.

We also need to enable farmers to contribute effectively to soil health management in partnership with policymakers, researchers, and the general public. To achieve this, we need to work with farmers to identify methods that work best for them and develop simple, reliable, and inexpensive soil health toolkits that provide data that are clear and reproducible. Furthermore, soil health must go beyond individual data to include collaboration among stakeholders through communities of practice, empowering farmers to better connect and take responsibility for soil health on their farm to pass to the next generation. Citizen science has a clear role to play in facilitating this and empowering farmers to effectively monitor global soils using standardised approaches that compliment statutory and traditional monitoring. Citizen science monitoring of soil health will also support farmers in understanding the impacts of changes in management practises, putting them in control of understanding their own soils and supporting a shift towards farmer-led, data-driven decision-making.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/24/10254/s1: Table S1: Weblinks, cost, and time requirement for each of the presented soil assessment methods. Table S2: Weblinks for each soil health toolkit presented, and an overview of target audience, accessibility, and geographic scope.

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