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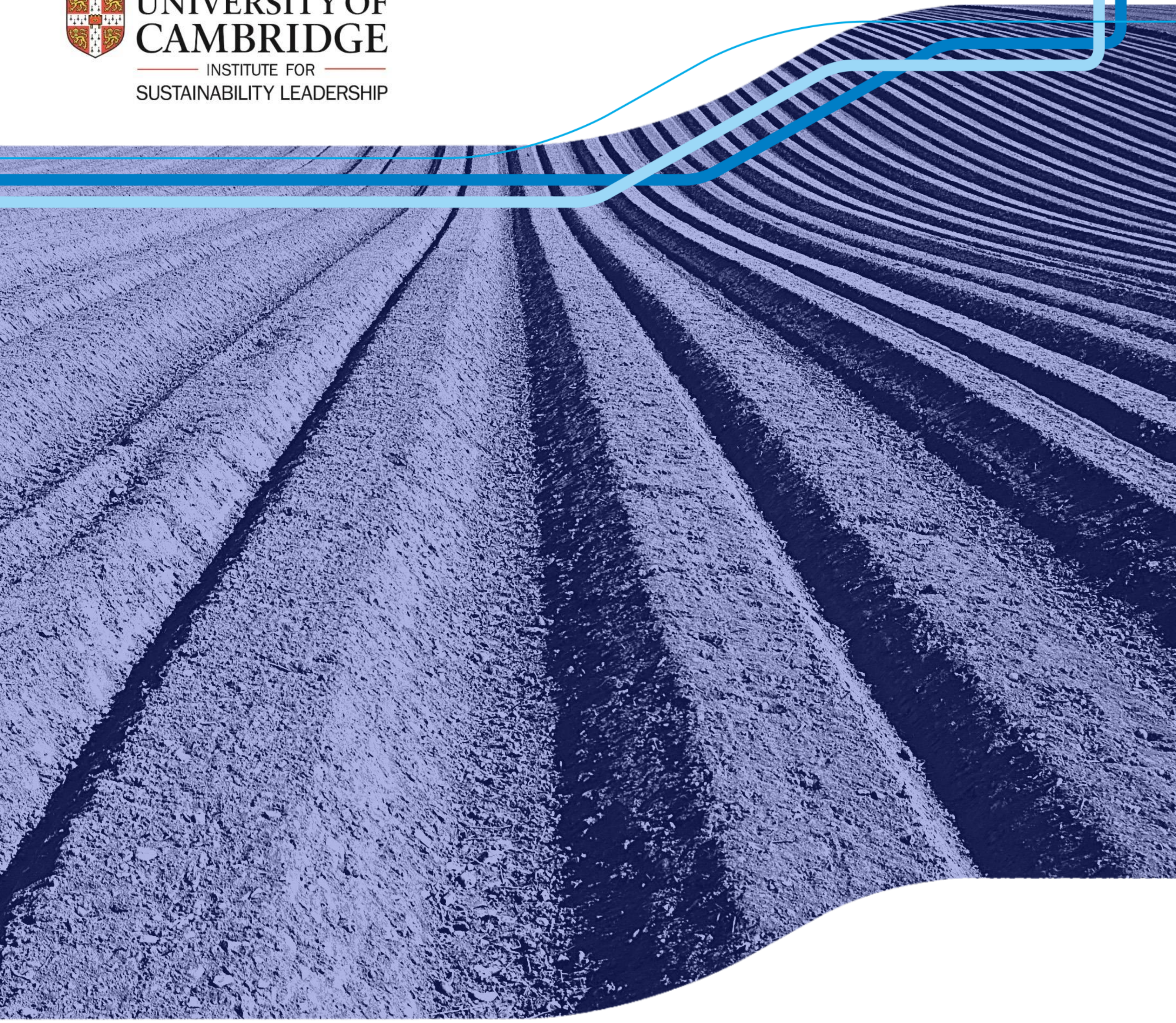

Soil health: evidence review

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Executive summary

Many leading organisations in the food and beverage sector have demonstrated progress in managing natural capital impacts in their direct operations, including greenhouse gas emissions and waste. Many recognise, however, that the largest impacts occur in their upstream value chains, particularly on farms where raw materials are produced. A key natural capital resource is soil, and managing soil health is one way in which businesses may be able to reduce their negative impacts on land use.

In an agricultural context, 'soil health' may be defined as a soil's capacity to respond to agricultural intervention, such that it continues to support the provision of ecosystem services as well as optimising agricultural production. The scientific literature proposes a range of definitions for soil health, but converges on the idea that 'healthy soil' must not only meet a level of quality as measured by local or remote testing methods, but must also be managed in such a way as to not adversely impact the ecosystem in which it is embedded.

This report proposes a functional definition of soil health, wherein healthy soil is defined as:

- suitable for agricultural production that is able to reach a competitive and sustainable yield
- stable or improving in measurable quality (physical, chemical, biological properties) over time
- not adversely impacting its ecosystem as a result of the land use activities to which it is subjected.

The report then addresses how businesses that depend on healthy soil may best demonstrate and hence manage their impacts. It recommends the development of a soil metric using a conceptual model that combines both a measurement of inherent soil quality as well as a measurement of land use type/intensity. Such a metric is intended to readily demonstrate the effects that any changes in land use practices may be having on soil health, be they positive or negative.

The soil quality literature provides a range of 'bottom-up' approaches and indicators for measuring inherent soil quality *in situ*, many of which require on-site access and assessment either in the field or in laboratories. The report concludes that although these indicators provide the most accurate results, businesses that are not in a position to acquire the requisite data may need other means of estimating soil's key physical, chemical and biological properties.

To derive a metric for soil health, it is suggested that businesses begin by taking a 'top-down' approach to measuring inherent soil quality using soil organic carbon (SOC). It may then be possible to calibrate this against other approaches such as soil biodiversity as scientific consensus emerges in this area. Verification in the field for critical supply chains may then be performed using a bottom-up methodology, along with means of assessing land use type/intensity that may be available.

It is recommended that investigations into the viability of SOC and other measures begin in the context of the University of Cambridge Institute for Sustainability Leadership (CISL) Natural Capital Impact Group – Soil Workstream, with a small group of like-minded businesses coming together to share insights on their own operations, objectives and data, to understand the means of measuring soil health that may be most beneficial to soil management.

Contents

1. Introduction

1.1. Overview

CISL performed an information gathering process to collate and review evidence on the current scientific understanding and assessment of soil health.

Many organisations in the food and beverage sector wish to inform decision-making on agricultural activities within their supply chains for which land and soil are natural capital impacts/dependencies, and are eager to do so using a clear scientific basis to help them draw conclusions and assign targets.

This report outlines a range of available approaches to soil health that have reached varying levels of scientific acceptance, and clarifies which of these approaches may be most suitable for businesses looking to apply a methodology to their own operations and supply chains.

For decision-making purposes, it is considered that business requires a high-level understanding of the variety of existing soil quality indicators and also their efficacy and reliability, and the availability of appropriate data and tools that have attained scientific consensus. Using this information, business may then be able to derive soil health metrics, and subsequently set sustainability targets.

The report references information contained within the Soil Health Review, a literature review produced for CISL on soil health and quality. The Review provides an informative basis for approaches to measuring the physical, biological and chemical properties of soil, and in particular addresses the availability of soil health metrics for data acquired *in situ*.

1.2. Objectives

The objectives of this summary report are to:

- establish a context for understanding soil health that is relevant to business
- propose a conceptual framework for understanding how soil health metrics may be derived by combining indicators of soil quality with those for land use type and intensity
- review and evaluate tools, data and indicators for soil quality assessment
- recommend an approach that enables businesses to move to the next step of including soil health within sustainability frameworks.

1.3. Scope

This report summarises the current state of scientific research on soil health and the various techniques used to acquire soil quality data. The report makes general recommendations based on several assumptions regarding goals and decision-making processes that are considered likely to be applicable to business.

2. Background and context

2.1. Overview of soil health

Soil is material found on the surface of the earth that comprises mineral particles, organic matter, water and air. Soil is a dynamic, living resource with a complementary interaction of biological (concerned with soil-inhabiting organisms, their functions and their activities), chemical (concerned with the chemical constitution, properties and reactions) and physical (concerned with the physical properties associated with structure and material/water transport) components.

The structure and composition of soil varies greatly, as does the size of its constituent particles. Mineral particles are divided into three broad classes: sand, silt and clay. On a practical level, soils are often termed heavy, medium and light as a means of classifying them according to different particle sizes. Soil characteristics typically change gradually over a landscape, and a variety of classification and taxonomy systems are used to describe these changes.

In an agricultural context, soil health may be defined as a soil's capacity to respond to agricultural intervention, such that it continues to support the provision of ecosystem services as well as optimising agricultural production. The definition is closely linked to that of 'soil quality', which refers to the condition and properties of a soil, often relative to the requirements of one or more species, including humans. Soil quality also refers to the dynamic nature of soil, in other words to properties that are affected by land management practices.

Using the above definitions, it may be tempting to oversimplify soil health by considering soil only in terms of the benefits it offers through agricultural productivity. However, such an oversimplification would omit both the temporal and geographical scales over which soil influences entire ecosystems, and not give due consideration to the nuances of soil's inherent biological, physical and chemical qualities.

2.2. Soil functions

The sustainable management of soil demands a similar approach to that taken for all forms of natural capital, balancing many interrelated challenges including those relating to climate, erosion, land degradation, pollution and biodiversity. Soil is a component within a dynamic ecosystem that includes terrestrial flora and fauna, water, nutrient and carbon cycles, and a range of other environmental processes. Within that ecosystem soil is considered to perform the following functions:

- provide physical support to plants
- regulate water, oxygen and solute flow for primary production
- provide a habitat for soil organisms, a key role in improving soil health
- regulate hydrological and mineral/nutrient cycling, a key role for the global climate
- detoxify organic and inorganic substances, a key role in water filtering/purification
- resist erosion.

A truly healthy soil should hence be defined as one for which these multiple functions are optimised. Fulfilment of only one function without the others may result in detrimental ecosystem effects. For example, significantly increasing nutrients via fertilisers for agricultural production may lead to increases in crop productivity, but could also result in the contamination of waterways by runoff.

Fortunately, many of the above functions are directly related to the inherent properties of soil. This means that a scientific basis exists for measuring a selected set of physical, chemical and biological soil properties that often correlate with a soil's ability to fulfil one or more ecosystem functions. Expert opinion converges on several parameters that are required for drawing conclusions on soil quality and also on methods for the acquisition and interpretation of data.

Considering soil only in terms of its inherent physical, chemical and biological properties is insufficient to provide a complete picture of soil health. A more robust approach would be to consider soil and the land (site) on which it is situated in terms of both soil quality and land use type/intensity, so that impacts resulting from land management activities can be incorporated into the definition.

2.3. Basis for identifying and evaluating metrics

Although definitions of soil health and soil quality are intuitively well understood, a globally applicable definition and a universal method for assessment have not yet obtained scientific consensus. Some of the reasons for this are:

- variation in the goals of land/ecosystem management and in the audiences to whom definitions may be applicable or appropriate
- few scientifically validated methods for measuring soil's integrated 'system' properties exist
- multiple possible methods for 'reductionist' soil health measurements are available
- variety in tools and data applied
- environmental variability over a range of geographical and temporal scales
- understanding of the capacity of soil to function under stress and disturbance is scant.

Scientific evidence appears to be strongest in the domain of *in situ* soil quality management and assessment, particularly those methods that take a reductionist approach to measuring soil physical, chemical and biological properties. A multitude of tests of varying efficacy and reliability are available, many of which have been tested in a variety of settings. Many of these are captured in detail in the Soil Health Review and summarised in this report.

In a decision-making context, it is recognised that businesses may not have full disclosure or access to the specific sites/farms from which they are procuring raw materials, making it difficult to measure soil quality at site level across their supply chains. Hence, businesses are likely to be interested in other emerging approaches that attempt to measure soil quality using remote techniques such as agricultural mapping, including satellite imagery.

For remote measurements of this type, it seems that scientific understanding and data availability are less developed and consensus less clear. Should businesses wish to apply such approaches (eg satellite measurements, mapping and precision farming techniques), this will likely necessitate taking a conservative stance to quantifying outputs, and a careful approach to drawing conclusions and communicating them to internal and external stakeholders.

2.4. Identify impact metrics

Metrics that businesses may identify for measuring soil health may eventually be communicated to both internal and external business stakeholders, including wider society. It is hence paramount that selected metrics are sufficiently robust, and where scientific consensus is lacking, caveats are included to justify specific conclusions. It is also necessary for businesses' own understanding to be clear on the power of particular metrics for later use in developing performance targets.

A recent review of metrics by CISL which included surveying businesses to understand their reporting needs highlighted a strong desire for common metrics for biodiversity, soil and water to help them shape operational decision-making, comply with regulatory demands and respond to investor requests. Businesses agreed that metrics should follow the key principles shown in Table 1.

Principle	**Description**
Meaningful	Meaningful to business and investor communities so it can be used to drive decision-making. Methodology is clearly understood
Measurable and comparable	Allows for comparison across geographies and time
Possible to aggregate	Can be aggregated from site level to regional and global scales
Practical	Data is accessible, measurable by a company or using free, globally available data. Ability to substitute better information where available
Replicable and credible	Based on a reputable scientific method
Context based	Considers local conditions/levels to reflect 'impact' (beyond 'usage')
Responsive	Responds to changes in company activities, both short and long term

Table 1: Key principles for biodiversity, soil, water and carbon metrics

It is considered that any soil metrics that are developed should follow similar general principles. The recommended metric approaches are assessed using these principles in Appendix A.

When considering which types of metrics would be most useful to business in terms of understanding and managing soil health, they should include, as a minimum, the possibility to assess and compare soil health with respect to, for example:

- status – is a site's soil health degrading, stable or improving?
- geography – how does a site's soil health compare with that of other sites in the region/globally?
- land management activities – how does an activity positively/negatively impact soil health?

All metrics will hence require status baselines to be established. The philosophy for setting these baselines is considered to be an area for further discussion and research, and is not addressed in detail in this summary report.

3. Soil health assessment

3.1. Proposed framework

A key question for businesses is how to demonstrate their impacts on soil health. This report asserts that good practice environmental stewardship is guided by an overarching goal of responsible and sustainable agro-ecosystem management, within which soil health is defined in a broad sense. To arrive at this goal, a simple framework for characterising healthy soil is proposed, comprising three related criteria:

Proposed healthy soil criteria

A healthy soil is one that is:

- suitable for agricultural production that is able to reach a competitive and sustainable yield
- stable or improving in measurable quality (physical, chemical, biological properties) over time
- not adversely impacting its ecosystem as a result of the land use activities to which it is subjected

Productivity criterion*: suitable for agricultural production*

The first criterion is easily understood and can likely be fulfilled with knowledge businesses already have available. If companies source from agricultural assets, then it follows that these assets are producing at acceptable yields, because this is what makes them commercially viable. If they were not, then companies would presumably divest these assets or switch suppliers.

Soil quality criterion*: stable or improving in measurable quality*

In general, businesses currently lack a clear understanding of this criterion. More understanding can, however, be achieved by embarking on a programme of collection and analysis of data using a minimum data set (MDS) of soil quality indicators. This is outlined in the Soil Health Review.

'Measurable quality' must be understood not only in terms of agricultural productivity, because this is already captured by the first criterion, but also in terms of physical, chemical and biological soil properties, as compared with pre-determined temporal and geographical baselines. This will involve developing a plan for periodic data acquisition and analysis (temporal), which may also include nearby assets (geographical), such as local farms, and data from regional/global maps.

Land use criterion*: subject to land use activities with acceptable impacts*

The third criterion requires a measure of land use intensity and land use type as part of any metric that may be used to quantify soil health, to account for land management activities. This will enable businesses to test strategies to secure soil health.

Several points need to be clarified here, not least what is meant by adverse impact. However, once these points are agreed, businesses will have a framework for understanding both negative and positive outcomes of their activities.

3.2. Conceptual model for soil health

To derive a metric for soil health, it is proposed to individually derive metric(s) for the two key soil health criteria suggested in the soil health decision-making framework, that of *soil quality* and *land use,* and then try to combine them in a common metric, using scientifically credible and data-supported assumptions, together with expert judgement. The conceptual model for this approach is shown in Figure 1; its elements are outlined in the following sections. The approach should lead to one or more soil health metrics that can take into account farming effects on the ecosystem.

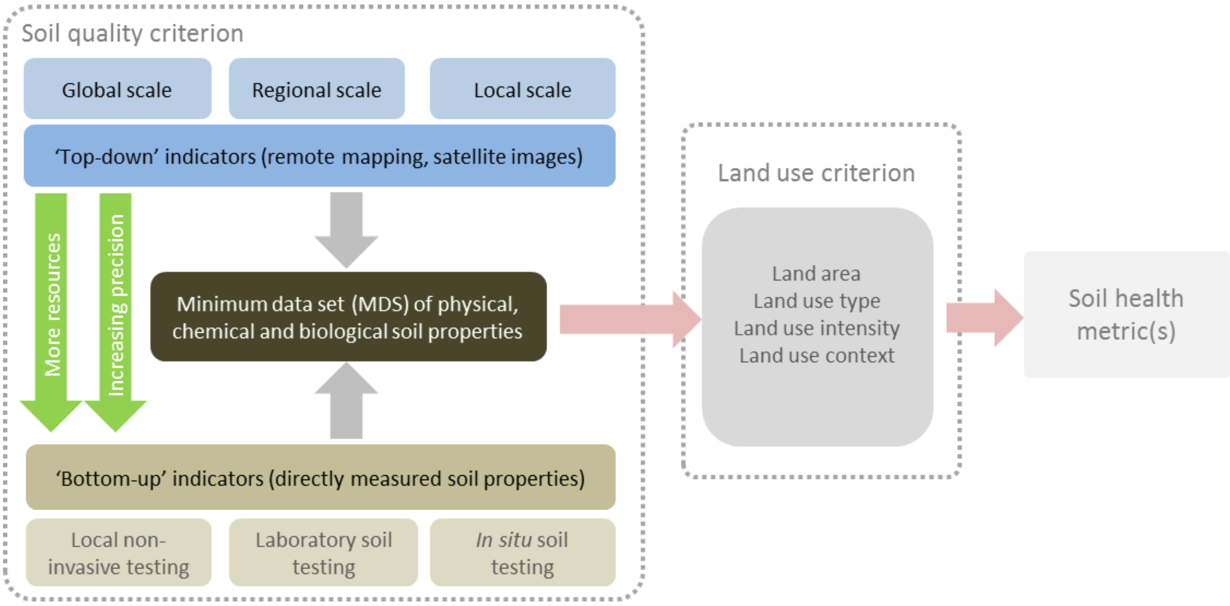

Figure 1: Conceptual framework for developing soil health metric(s)

3.3. Soil quality criterion

Establishing indicators

This report reviews several measurements of soil quality properties termed indicators. Within the soil science community, the minimum number of indicators required to draw robust conclusions regarding soil quality is referred to as an MDS. Traditionally, all of these indicators have been measured with bottom-up methods like *in situ* and laboratory soil testing and, increasingly, local non-invasive testing, such as measurements taken in the field using tractor-mounted equipment. Soil quality is rated as favourable if values acquired for a number of soil properties fall within specified ranges, or if expert opinion judges it to be so.

More recently, techniques for the 'remote' measurement of a limited number of indicators have started to gain acceptance with the advent of precision farming methods and satellite-acquired data. Other remote measurements can be made by using globally available data sets and maps. Although these top-down indicators have not yet achieved widespread scientific consensus, some of them are proving effective for understanding soil quality. It is anticipated that interest in these indicators will continue to grow, particularly as technology advances and accuracy is improved.

The key difference between bottom-up and top-down indicators, from a practical perspective, is that bottom-up indicators require significantly more resources to acquire data but offer a higher level of precision. Bottom-up indicators are also much more widely accepted, and hence numerous methods and data exist against which to validate results. Top-down indicators, on the other hand, can potentially provide a means of adding geographical and temporal context to local soil quality measurements by comparing them with regional and global data; they also reduce the need to know the precise sourcing locations and to have access to sites to undertake direct soil tests. A top-down approach would allow rapid access to data without having to undertake on-site measurements.

Examples of top-down approaches

Soil organic carbon

One example of a top-down approach is to use globally available maps for SOC; this is considered to be a useful proxy for soil quality and is available without undertaking *in situ* assessment.

Global maps may offer businesses an approach to begin measuring soil quality based on the known geographical locations of their suppliers. The disadvantage of SOC is that changes in SOC can take many years to manifest, making it a slow indicator of change. Factors including temperature, rainfall, soil type and management all influence SOC content and accumulation rates. Although SOC can be useful as a simple single indicator, its appreciable limitations must be taken into account if it is used in isolation.

Another recent example of global mapping comes from the United Nations Environment World Conservation Monitoring Centre (UN Environment Programme – WCMC), which has developed a first estimate of global maps of natural capital. This builds on a considerable body of work in the fields of natural capital accounting and the mapping of ecosystem services, including the UN Statistics Division System of Environmental-Economic Accounting (SEEA) and Experimental Ecosystem Accounting approaches. The soil map contains layers of key soil qualities derived from the Harmonised World Soil Database [1] (Figure 2). This and other systems may be of interest (refer to Appendix C).

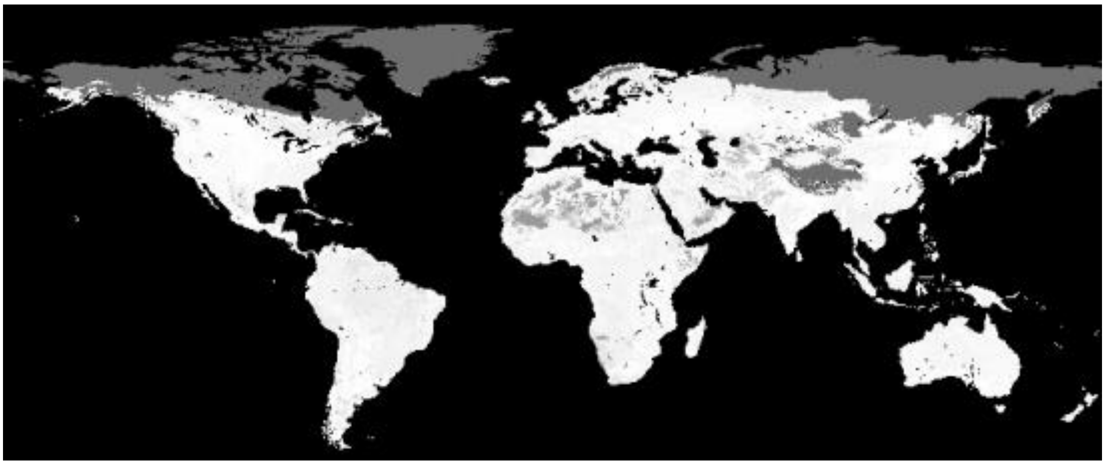

Figure 2: Map of soil organic carbon to a depth of 1 metre – darker areas indicate higher carbon stocks [2]

Digital soil mapping is an approach used to predict spatial patterns of SOC stocks across various spatial and temporal scales based on land use, local terrain, climate and soil type characteristics, [3] which could enable a more accurate assessment of the impact of land management practices on SOC. Although such models are currently unavailable at the global scale, businesses may be able to use the results of regional studies. The European Commission's Joint Research Centre has developed models and maps for both current and projected SOC for Europe, [3,4] and there are similar models for China [5] and the region of Andalusia in Southern Spain,[6] which may be of interest. It is important to note that the land use types within the models are restricted to the general categories of: arable lands, forest lands, pastures and wetlands, which may be too broad-ranging to assess the effects of changes in intensities of management practices. It is recommended that businesses investigate the different mapping options and decide on the most optimal available, as part of their involvement in the Natural Capital Impact Group – Soil Workstream.

Soil biodiversity

Another indicator of soil health is earthworm counts, a measure of soil biodiversity. This type of measure typically requires detailed *in situ* data acquisition. However, global maps of soil biodiversity also exist, and indices of threats to soil biodiversity produced by the European Commission Joint Research Centre [4] offer an alternative top-down approach for assessing soil health, providing that the geographical location is known. Maps of soil biodiversity (Figure 3) are based on two data sets: the distribution of microbial soil carbon (a proxy for soil microbial diversity) and the distribution of the main groups of soil macrofauna (a proxy for soil fauna diversity).

Figure 3: Map of soil biodiversity – darker areas indicate higher biodiversity (European Commission Joint Research Centre)

The European Commission Joint Research Centre's [4] soil biodiversity threat map (Figure 4) comprises a range of data sets describing different threats to soil biodiversity:

- loss of above-ground (plant) biodiversity
- pollution and nutrient overloading (based on nitrogen fertiliser application)
- agricultural use (cropland percentage cover)
- overgrazing (cattle density map)
- fire risk (based on fire density)

- soil erosion (using water and wind erosion vulnerability indices)
- land degradation (based on the desertification vulnerability index)
- climate change (based on the global aridity index)

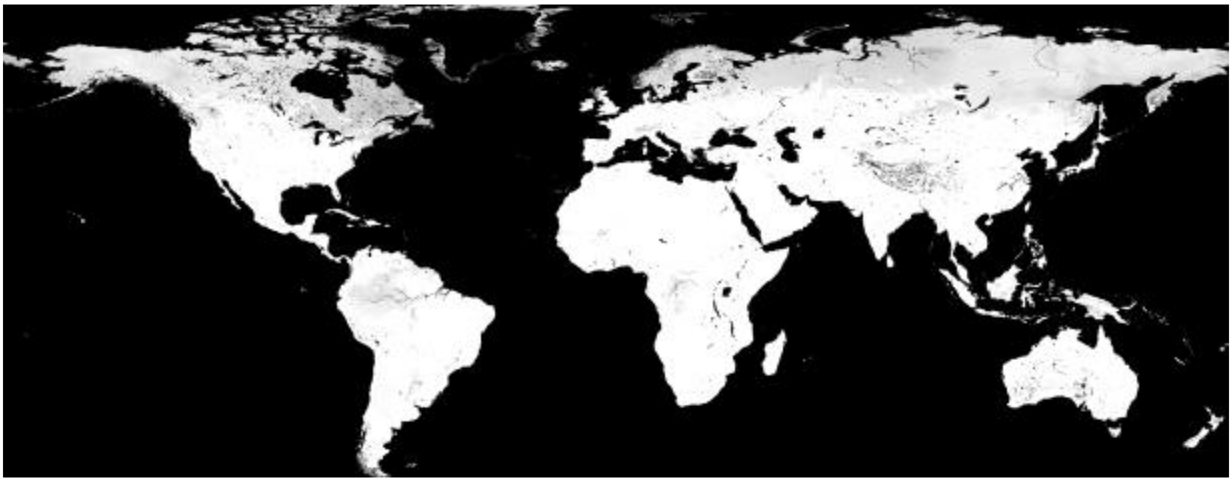

Figure 4: Map of threats to soil biodiversity – darker areas indicate higher threat (European Commission Joint Research Centre)

One additional piece of new research has demonstrated the links between soil biodiversity and the type of land and land use intensity (based on the methodology used for the biodiversity intactness index [7]).

Conclusion for top-down approaches

Global maps may provide a useful approximation for measuring impacts on soil health, and two options are recommended: SOC maps and biodiversity maps.

The advantage of using the soil biodiversity approach is that there are maps of both global soil biodiversity and global threats to soil biodiversity; this could provide an up-to-date indication of the hotspots of soil sensitivity across supply chains. Such maps, combined with a coefficient indicating the level of impact that specific land uses and land use intensities have on soil biodiversity, could provide a direct link between land management practices and soil health. This would offer businesses the flexibility to explore different improvement approaches within the model.

If SOC is selected, it would be useful to explore whether literature and data exist that link the impact of land use type and land use intensity to changes in SOC, so that the metric can be used to test alternative strategies. Without the link between land management practices and soil quality, businesses will have no clear means of demonstrating that changes in approach to management can effect improvements in sustainability performance and yield.

Examples of bottom-up approaches

There are several means of undertaking bottom-up assessments, each of which requires an interpretation of the measurements. Some measures have defined suitability ranges (eg bulk density or earthworm numbers), some have a general association with changes in soil function (eg root growth in relation to penetration resistance or soil nutrient index), whereas others provide trajectories assessment (eg soil organic matter/carbon). In addition, some provide a relatively representative measure (eg visual evaluation of soil structure or visual soil assessment) and others are more explanatory to help contextualise other variables (eg location, pH, crop or yield data). Scoring systems are in place for the main commercial soil quality tests, and may be best interpreted using a 'traffic light' type system, which provides a coarse rating of the variable in terms of high/medium/low quality.

Minimum data set and soil quality metric(s)

Scientific consensus on soil quality measurement converges around the concept of a Minimum Data Set (MDS). The Soil Health Review provides more details on the MDS and scientific references for it. A number of indices have been developed over the past two decades by different authors, which prioritise different indicators as part of overall assessments of soil quality. These include SOC indices, enzyme activity indicators of organic matter and a microbiological degradation index, to name a few. Once an MDS has been established and input with data, expert opinion and/or statistical techniques (eg principal component analysis) can be applied to derive soil quality indices/metric(s).

Appendix B presents an overview of indicators for soil quality assessment, including rationale. Scientific consensus on the potential value of a particular indicator/technique for inclusion in a soil quality metric is presented using a star (*) system, with five stars being assigned to those with greatest accuracy and efficacy. Indicators are separated into physical, chemical and biological soil properties. The 'Type' column shows which of the indicators described have been traditionally included in an MDS within soil science literature. Indicators that appear less frequently in the MDS according to the literature have been classified as 'Optional', whereas 'Proxy' is applied if an indicator is able to arrive at soil property characterisation via other means. Types of assessment may be in field (manual or remote sensing), laboratory and maps/satellite.

Appendix A provides a subjective appraisal of the main bottom-up approaches suggested against a set of principles. The most favourable of these are considered to be as follows:

- Cornell Soil Health Test
- Haney Soil Health Test
- Visual Soil Assessment (VSA) test

Appendix B presents a summary of reductionist model inputs (MDS) based on the indicators they include being rated higher or lower based on the star (*) system. This analysis concludes, unsurprisingly, that it is better to combine approaches that have higher ratings than to base soil quality measurements on less indicators.

Conclusion for bottom-up approaches

It is concluded that bottom-up indicators can be useful, but require on-site access with assessments primarily being undertaken in the field or in laboratories. It is concluded that although such assessment will provide the most accurate metrics, it may not be the most appropriate approach. A top-down approach is recommended to begin the process of measurement, with verification being carried out in the field for critical supply chains using a bottom-up methodology as more data becomes available.

3.4. Soil-based data sets, maps, models and other resources

Several methods of measuring soil quality are emerging from top-down approaches. An overview of a variety of data sets, maps, models and other resources that contribute to serving this purpose is provided in Appendix C. These resources have been letter-coded by type as follows: data sets (D), maps (M), models (Md) and other resources (O). The use of these methods must take into account data resolution, scale of acquisition, patchiness in terms of coverage by country and region, and in some cases questionable levels of accuracy. Caution is therefore required when selecting approaches, and gaining expert advice is recommended.

3.5. Land use criterion

Although the *soil quality* criterion focuses on deriving a metric for soil based on its inherent physical, chemical and biological properties, the *land use* criterion is concerned with deriving a metric that captures the impacts that land management activities have on the soil and ecosystem at an agricultural site.

Although correct land management practices can in general contribute to improved soil properties and high crop yields, incorrect practices may increase soil degradation, including poor soil structure, salinity and erosion. In its natural state, soil rarely provides the most favourable conditions for crop growth. Management practices that enhance growth include: cultivation, crop rotation, liming, residue management, organic and inorganic fertiliser application, and cover cropping. The same practices, incorrectly applied, may have negative impacts on the site and surroundings including emissions (eg methane), waste (eg agrochemical) and discharges (eg runoff with a high nutrient content).

By incorporating a land use metric into an overall metric for soil health, land management practices can, to some extent, be accounted for. Understanding land use would include temporal and geographical context, by comparing soil quality and status over time (eg does the parameter improve, remain neutral or reduce) and between locations (eg is the parameter better, equal or worse than at a similar location). In other words, 'pressure' on the environment and 'response' from management practice would need to be incorporated into calculations.

It is possible to link land use to soil quality and develop a coefficient that could be implemented to estimate its impact on soil. New research has been undertaken that demonstrates how land use type and land use intensity combine to impact soil biodiversity. Within this research, land use type is categorised as:

- primary vegetation
- recovering/secondary vegetation
- plantation forest (ie timber, fruit, oil palm or rubber)
- cropland
- pasture
- urban

Land use intensity is categorised into three levels (minimal, light and intense use).

This data could be used to provide a coefficient that could be applied to estimate the loss of soil biodiversity, and thereby the impact upon soil health.

It should be possible to design a decision tree and set of questions that would determine the selection of the appropriate coefficient. It is likely that this could be automated as much as possible to minimise the burden on staff.

This is new research that has not yet been peer reviewed. Businesses are advised to keep a watching brief on this and to initially focus their efforts on SOC.

4. Conclusions and recommendations

4.1. Conclusions

This summary report defines soil health in a way that provides business with the possibility of measuring the sustainability of its agricultural activities in terms of both inherent soil properties and land use. The aim is to provide a clear overview of the level of scientific consensus that has been reached for the approaches described.

Available scientific literature provides strong consensus around several tools and techniques for obtaining indicators of soil quality. Many of these require *in situ* and laboratory tests, and some emerging methods allow data to be acquired remotely with an increasing level of precision, either as standalone indicators or to validate and enhance the value of indicators acquired in the field.

Using the conceptual model proposed in this report, it is envisaged that businesses could develop a metric or set of metrics for soil health that include soil quality and land use type and intensity. These metrics could then be used to assess businesses' impacts on soil and develop performance targets.

It is concluded that a top-down approach to defining a soil health metric be applied, and validated using data sets that are available to companies. One promising method of measurement is that of SOC, which can be estimated to an increasing level of precision via satellite mapping, as maps gradually become more available for different regions globally. It is hence recommended that businesses investigate this approach first.

The European Commission's map of global soil biodiversity is a further approach that could be considered. It may be possible to use new scientific research that models land use together with soil health using a proxy of soil biodiversity. Taking this approach will provide businesses with the flexibility to test new strategies, and the ability to adjust variables such as land use intensity within the model.

4.2. Next steps

In the future, it is recommended that businesses consider the following:

- Define soil health: adopt the definition of soil health provided in this report, including the three criteria outlined in the proposed framework in this report.
- Devise strategy: devise a strategy for developing metrics that includes the conceptual model proposed in this report as a starting point.
- Inform soil quality criterion: investigate the value of using SOC as a key top-down indicator of soil quality for input into a soil health metric, beginning by conducting an analysis of the most suitable global SOC maps. Determine site-specific, bottom-up assessments that could feasibly be performed (if any), using indicators within an MDS.
- Inform land use type/intensity criterion: develop a strategy for collecting data to understand land use type and intensity within supply chains. Where this is not possible, make robust assumptions based on information for known geographical locations.
- Develop a metric with like-minded peers: take advantage of the Natural Capital Impact Group – Soil Workstream to work towards developing and testing a soil health metric together with like-minded peers, promoting peer-to-peer learning to arrive at an optimal solution.
- Communicate effectively: Agree a strategy for communicating the approaches to understanding, measuring and managing soil health both internally and externally.

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Appendix A: Subjective appraisal of the main *in situ* approaches suggested against set of principles

Metric	Meaningful (to business)	Measurable and comparable (over time and locations)	Possible to aggregate (to a regional level)	Practical (to be measured)	Replicable and credible (regarding method)	Context based (accounting for scenario)	Responsive (to activity changes)
Commercial tests							
Cornell Soil Health Test	✓✓✓✓✓ Simple overall numeric score or traffic light	✓✓✓✓ Comparisons possible with some benchmarking	✓✓✓✓ Numeric values could be aggregated Interpretation may need benchmarking	✓✓✓ Simple process, but test requires field access, has a unit cost and needs a suitable laboratory	✓✓✓✓ Widely used and well-recognised test	✓✓✓ Effective, but remote test that can require further scenario information	✓✓✓✓ Changes mapped over time could show responses
Haney Soil Health Test	✓✓✓✓✓ Simple overall numeric score or traffic light	✓✓✓✓ Comparisons possible with some benchmarking	✓✓✓✓ Numeric values could be aggregated Interpretation may need benchmarking	✓✓✓ Simple process, but test requires field access, has a unit cost and needs a suitable laboratory	✓✓✓ Widely used and relatively well-recognised test	✓✓✓ Effective, but remote test that can require further scenario information	✓✓✓✓ Changes mapped over time could show responses
VSA test (Visual Soil Assessment)	✓✓✓✓✓ Simple overall numeric score or traffic light	✓✓✓✓ FAO scenario guidance, but potential benchmarking requirement as well for effective comparisons	✓✓✓✓ Numeric values could be aggregated. Interpretation may need benchmarking	✓✓✓ Field-based test requiring access, but can be carried out on site by unskilled staff	✓✓✓✓ Widely used and well-recognised test	✓✓✓✓✓ Carried out in the field to account for scenario	✓✓✓✓ Field test is responsive to season and scenario

Soil organic matter	✓✓✓	✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓✓	✓✓
	Context-specific percentage	Measurable and geographical averages are possible, but the meaning is questionable	Regional means are possible, but appreciable interpretation issues	Field or laboratory test, typically with a unit cost Requires location, equipment and potentially field access	Recognised, but has limitations as a health test	Responds to scenario and management	Responsive, but only on a longer time frame (many years)
Reductionist model							
Model approach	✓✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
(mainly 3–5 star options)	Traffic light based on strong indicators	Scenario comparisons possible, potentially with benchmarking	Potential for simple overall traffic-light or heat maps	Rating is dynamic: depends on the options chosen and system	Higher rating linked with stronger options	Higher rating linked with stronger options	Higher rating linked with stronger options
Model approach	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
(mainly 2–4 star options)	Traffic light based on moderate indicators	Scenario comparisons possible, potentially with benchmarking	Potential for simple overall traffic-light or heat maps	Rating is dynamic: depends on the options chosen and system	Ratings linked with moderate options	Ratings linked with moderate options	Ratings linked with moderate options
Model approach	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓
(mainly 1–3 star options)	Traffic light based on lesser indicators	Comparisons possible, but would be based on lesser indicators	Potential for simple overall traffic-light or heat maps	Rating is dynamic: depends on the options chosen and system Practical options tend to be higher starred	Ratings linked with lesser options	Ratings linked with lesser options	Ratings linked with lesser options

Appendix B: Indicators for measuring soil quality

Type	Indicator	Rationale for assessment	Type of assessment	Method of assessment	Consensus on value
Physical					
MDS	Soil texture/structure	Used to make inferences regarding soil susceptibility to erosion and level of soil compaction and variability Can be used to understand water and chemical retention and transport	In field – manual	Visual Soil Assessment (VSA) test In-field assessment of key soil and crop performance indicators of soil quality	*****A wider soil health test that assesses more than just structure
			In field – manual	Visual Evaluation of Soil Structure (VESS) test In-field assessment using a semi-quantitative tactile method	***Can give good 'traffic light' soil structure information
MDS	Water-holding capacity	Water-holding capacity describes water retention, transport and soil susceptibility to erosion	In field – manual Laboratory	Mainly field sampling and laboratory assessment	Unknown
MDS	Soil rooting potential	Soil rooting potential indicates potential productivity	In field – manual	For rooting potential, a penetration resistance test may be employed manually in the field using a cone penetrometer	**Could be used to 'traffic light' soil structure
MDS	Infiltration and soil bulk density	Bulk density used to gauge suitability for root growth Comparisons made to critical values Provides data for soil structural comparison	In field – manual In field – remote sensing	In-field assessment for infiltration and bulk density In-field remote sensing for bulk density only	*****Well-recognised, comparable metric
Optional	Erosion/ waterlogging		In field – manual Maps/satellite	Can be assessed at a range of scales from manual field assessment through to satellite imagery	Unknown Requires ground truthing
Proxy	Soil organic matter (SOM), grain nutrient content and yield in combination	May give an indication of likely soil condition	In field – manual In field – remote sensing Maps/satellite	In-field or post-harvest assessment or potentially in-field remote sensing	Unknown Requires ground truthing

Type	Indicator	Rationale for assessment	Type of assessment	Method of assessment	Consensus on value
Chemical					
MDS	Soil organic matter (SOM).	Can be a proxy/guide for soil fertility and nutrient availability SOM is the organic soil fraction exclusive of undecayed plant and animal residues Soil organic content (SOC) is the largest single chemical constituent of SOM (~58%)	In field – manual Laboratory In field – remote sensing Maps/satellite	Mainly field sampling and laboratory assessment, although remote sensing (potentially field based and aerial/satellite systems) starting to become available It should be noted that SOM is slow to respond to change so assessment is often periodic	*****Tests at the field level are generally the strongest approach Satellite sensing would lessen field accuracy and reduce the star rating (larger regional maps would be of very limited use)
MDS (explanatory variable rather than true 'indicator')	pH	Biological and chemical activity thresholds Soil pH is important for nutrient availability; most nutrients are available to plants in the pH range 6.5–7.5, which is generally very compatible with plant root growth	In field – manual Laboratory	Field sampling and (mainly) laboratory assessment, although some field-testing kits are available	Is not a strong measure of soil health/quality in its own right, but provides useful background and context
MDS	Electrical conductivity	Used as an indirect indicator of the amount of nutrients available for plant uptake and salinity levels, and as a surrogate measure of salt concentration, organic matter, cation-exchange capacity, soil texture, soil thickness, nutrients (eg nitrate), water-holding capacity and drainage conditions	In field – manual In field – remote sensing	Collected through manual means or remote sensing in the field	**Could be used to 'traffic light' soil structure
MDS	Extractable nitrogen	Indicates soil reserves and potential plant productivity Can also be related to leaching and environmental risks	In field – manual Laboratory In field – remote sensing	Soil nitrogen (N): mineralised N (N-min), ammonium (NH_4^+), nitrate (NO_3^-) Through field/laboratory assessment or potentially in-field remote sensing	***Can be informative but is also variable and difficult to interpret depending on timing
			Laboratory	Grain nutrients	****

Type	Indicator	Rationale for assessment	Type of assessment	Method of assessment	Consensus on value
				Assessment of grain (other produce sample) for key selected nutrients or nutrient ratios [eg ratio of nitrogen to sulphur for wheat; or phosphorus content for grain]	
MDS	Phosphorus	Indicator of potential plant productivity and environmental quality/risks	In field – manual Laboratory In field – remote sensing	Soil phosphorus (P) Through field/laboratory assessment or potentially (mainly) in-field remote sensing	*****Some interpretation of total and available nutrients is needed as well
			Laboratory	Grain nutrients Assessment of grain (other produce sample) for key selected nutrients or nutrient ratios [eg ratio of nitrogen to sulphur for wheat; or phosphorus content for grain]	****Could be informative but is also variable and would need ground truthing
Optional	Potassium, other nutrients	Component indicators of potential plant productivity and environmental quality	In field – manual Laboratory In field – remote sensing	Macro-nutrients: potassium (K), magnesium (Mg); micro-nutrients: iron (Fe), copper (Cu), boron (B), manganese (Mn), etc. Through field/laboratory assessment or potentially (mainly) in-field remote sensing	**Difficult to interpret and value varies with crop and scenario
Optional	Cation-exchange capacity	Can be a proxy/guide for soil fertility	In field – manual Laboratory	Typically field sampling and (mainly) laboratory assessment	Unknown
Optional	Salinity	Assessment of soluble salt in soil; excess can adversely affect crop growth	In field – manual Maps/satellite	Can be assessed at a range of scales; often field based but remote sensing is becoming more available	**Can be of value in certain scenarios
Optional	Detailed soil chemistry	Indication of nutrient availability, and hence productivity and	In field – manual Laboratory	Laboratory or in-field testing possible; often involves very detailed laboratory	*Can be difficult to interpret; only used when

Type	Indicator	Rationale for assessment	Type of assessment	Method of assessment	Consensus on value
		environmental quality		tests	looking at very specific soil/crop rotation scenarios
Proxy	SOM, grain nutrient content and yield in combination	May give an indication of likely nutrient availability	In field – manual Maps/satellite	Would need data sets and ground truthing	Unknown
Proxy	Other options for some crops (eg nutrient budgets or visual deficiency symptoms)	May give an indication of likely nutrient availability	In field – manual Maps/satellite	Would need data sets and ground truthing	Unknown
Biological					
MDS	Soil Organic Matter (SOM) SOC is the largest single chemical constituent of SOM (~58%)	Used as a proxy for soil fertility and nutrient availability SOM is considered integral to sustainable agricultural production	In field – manual Laboratory Maps/satellite	Mainly field sampling and laboratory assessment Remote sensing (potentially field based and aerial/satellite systems) starting to become available – eg Diffuse reflectance spectroscopic techniques	*****Remote-sensing techniques have great potential for mapping and temporal–spatial monitoring of SOM
MDS	Soil biology: macro- and microbiological indicators	Provides a rapid indicator response or early warning of management effects on organic matter or other aspects of soil quality	In field – manual Laboratory	Soil microbial assessment/profiling Field sampling and (specialist) laboratory assessment	*Typically require laboratory access and can be difficult to interpret
			In field – manual Laboratory	Number and diversity of macro- and micro-organisms, eg earthworm counts Field sampling and either in-field assessment (macro) or laboratory assessment (micro)	****Earthworms are a relatively well-recognised and accepted metric
			In field – manual Laboratory	Number and diversity of mycorrhiza and root colonisation Field sampling and (specialist) laboratory assessment	*Typically require laboratory access and can be difficult to interpret
MDS	Potentially	Describes soil productivity and	In field – manual	Field sampling and typically (specialist)	Can provide an estimate of

Type	Indicator	Rationale for assessment	Type of assessment	Method of assessment	Consensus on value
	mineralisable nitrogen	nitrogen supplying potential Situated within soil chemistry aspects of soil biology, and to an extent covered in 'Extractable nitrogen' (see above)	Laboratory	laboratory assessment	biomass, although other soil factors influence interpretation
MDS	Soil respiration	Defines a level of biological activity and can provide an estimate of biomass	In field – manual Laboratory	Soil respiration test Field sampling and (mainly) laboratory assessment, although some field-testing kits are available	**Some approaches can be a useful laboratory or field indicator, but they are often difficult to interpret
Proxy	Crop growth or other physical changes	May give an indication of biological impacts on production (eg fertile areas or areas damaged by soil pests)	In field – manual Maps/satellite	Assessment could be delivered through a range of approaches from field to satellite, but increasingly remote assessment	*Will need ground truthing and would be insensitive

Appendix C: Soil-based data sets, maps, models and other resources

Name *(main resource type)*	Location	Comment
Global Agro-Ecological Zones (GAEZ) *(type: M)*	http://www.fao.org/nr/gaez/en/	The FAO and the International Institute for Applied Systems Analysis (IIASA) have developed the methodology for assessing agricultural resources and potential. Services such as Ecocrop can provide information on the environmental requirements of a given crop: http://ecocrop.fao.org/ecocrop/srv/en/home
Australian Soil Quality website (*(type: M, D)*	http://www.soilquality.org.au	Provides a comparison portal where users can post their own soil information, resulting in the creation of partial data
European Soil Data Centre (ESDAC) *(type: D, M, Md)*	http://esdac.jrc.ec.europa.eu	This is a thematic centre for soil-related data in Europe and contains a number of resources that are organised and presented in various ways: including data sets, services/applications, maps, documents, events, projects and links
FAO Soils Portal *(type: D, M, O)*	www.fao.org/soils–portal	A source of information and knowledge on different components and aspects of soils (see http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/)
ISRIC World Soil Information *(type: D, M, Md, O)*	http://www.isric.org http://www.isric.org/explore/soilgrids	Information about global soil resources, free data sets and links to other portals such as the SoilGrids system: a collection of soil property and class maps of the world at 1 km and 250 m spatial resolution produced using soil mapping models
Landsat *(type: D, M)*	https://landsatlook.usgs.gov/viewer.html https://landsat.gsfc.nasa.gov/	Provides assorted spectral information on the earth's surface
'RothC model' *(type: Md)*	http://www.rothamsted.ac.uk	Rothamsted model concerned with carbon capture and turnover in soils
UK national data sets *(type: D, M, O)*	http://www.landis.org.uk/ http://www.soils-scotland.gov.uk/	Detailed national research data sets are becoming available; for example in the UK, the Defra open data strategy will facilitate the provision for freely available soil data gathered through the Sustainable Intensification Research Platform projects (http://www.siplatform.org.uk) looking at soil quality and soil management impacts. In addition, English data is available through services provided via the LandIS site, and Scottish soils data is also freely available
UNEP: The Benefits of Soil Carbon *(type: M, O)*	http://www.soilcarbon.org.uk/files/UYB_2012_CH_2-1.pdf https://wedocs.unep.org/rest/bitstreams/16348/retrieve	United Nations Environmental Programme (UNEP) information/reports on The Benefits of Soil Carbon, and Towards a Global Map of Natural Capital: Key Ecosystem Assets [2]
Global Soil Biodiversity Atlas *(type: D, M)*	http://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-atlas	The European Commission Joint Research Centre provides freely downloadable maps of global soil biodiversity and threats to soil biodiversity