AI4SoilHealth

INDICATOR SELECTION FRAMEWORK WITH PROTOCOL FOR AI4SOILHEALTH V2

D3.2

Version 1.1

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1.0	12/11/2025	• Initial version
1.1	21/11/2025	• Updated after internal review

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1. INTRODUCTION

Deliverable 3.2 (D3.2) of the AI4SoilHealth project, is aimed at designing new metrics for selecting soil health indicators (SHIs) for effective assessment and evaluation. Using the framework produced in Deliverable 3.1 (D3.1) as a template for soil indicator assessment, the objective of this deliverable is to review, examine and create a new robust framework for selecting SHIs as part of a probabilistic based monitoring structure.

This deliverable will assess new SHIs to address outcomes previously identified and discussed in D3.1 and provide an up-to-date robust framework for selecting SHIs designed on a set of agreed selection criteria. This will be significant in working towards meeting the eight European Union (EU) Mission Board targets set in the Soil Mission Implementation Plan. Additionally, the Mission Board identified eight SHI channels within which the proposed framework, can be used as a basis for testing and further improving these SHIs. Also, the SHI selection indicator criteria will be beneficial in selecting future SHIs, becoming fully aligned with the newly passed EU Soil Monitoring and Resilience Directive (Council adopts new rules for healthier and more resilient European soils - Consilium, 2025). Therefore, D3.2 will provide recommendations across other work packages (WPs) within the AI4SoilHealth project that align with future assessment, measurement and monitoring of soil health across the EU. Relevant publications described in **Appendix 1-3** were used as basis in drafting this deliverable.

1.1 Soil health Indicators (SHIs)

Soil health is a principal component of climate change mitigation with soil being the main reservoir of carbon (C) among terrestrial ecosystems and continuously contributing to soil C sequestration as well as the reduction of greenhouse gas (GHG) emissions. Soil health refers to the continued capacity of the soil to support vital ecosystem functions and services, biodiversity, food security and climate regulation in connection with the Sustainable Development Goals (SDGs) and European Green Deal (Radulov and Berbecea, 2023; Smith et al., 2021). Healthy soils are necessary for our environment, economy and society. Moreover, healthy soils, promoted through sustainable land management, will have a significant role in achieving some of the European Green Deal targets including sustainable farming and forestry, biodiversity, zero-pollution and climate resilience (Broothaerts et al., 2024).

Soil health refers to "*the biological, chemical and physical properties of the soil which determine its capacity to function as an integral component of the living system and its capacity to provide ecosystem functions*". This definition is based on the proposal of the Soil Monitoring and Resilience Directive (Soil Monitoring Law) (EC, 2023). In addition, the European Parliament Committee on the Environment, Public Health and Food Safety (ENVI) Report (EP, 2024) further defines soil health as "*the physical, chemical, functional and biological conditions of the soil which affects its capacity to function as a significant component of the living system providing ecosystem services taking land use into account*".

To assess and monitor the condition and overall health of soil, well-defined and measurable SHIs are required. In their report, Broothaerts et al., (2024), discussed SHIs at the EU-level. These were selected based on: (1) the main soil degradation processes and associated SHIs described in literature, (2) each of the specific objectives and SHIs of the Mission Soil Implementation Plan (**Figure 1.1**), (3) data availability, (4) comprehensive assessment of soil health by including as many as SHIs possible and (5) only one indicator for each soil degradation was retained.

To establish whether a soil can be considered "*healthy*" or "*unhealthy*", thresholds have been recognised for each indicator. These thresholds, established based on evidence described in scientific literature, can be considered as an estimate value at the point beyond which soils can be seen as significantly affected by a certain degradation process. In conditions when the soil reaches the threshold, the soil is described as unhealthy.

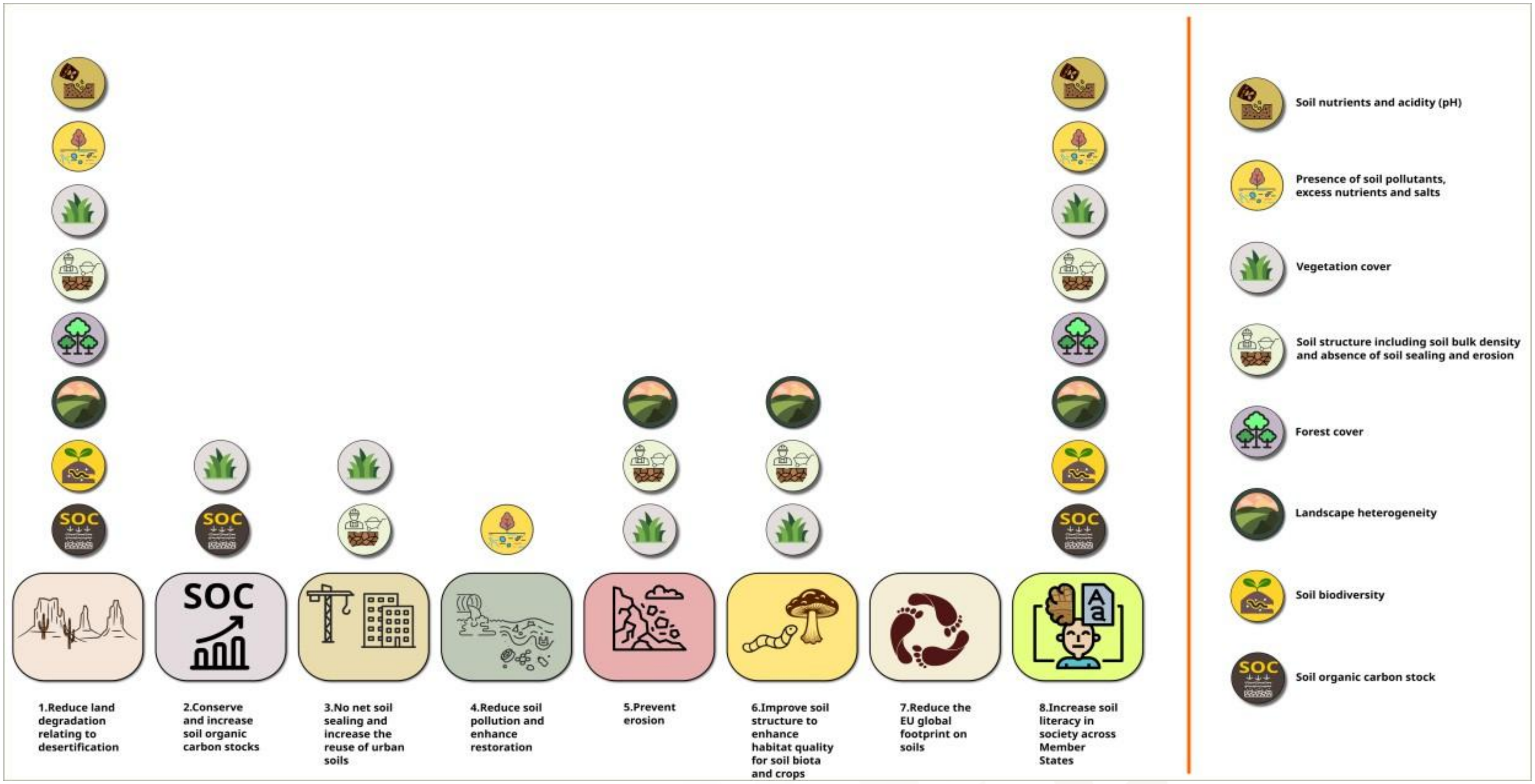


Figure 1.1. The Specific Objectives (bottom) and Indicators (right) of the Mission Soil Implementation Plan. Source: Mission Soil Implementation Plan (2030) and Panagos et al., (2024)

As discussed in the EU Indicator Framework 2024 report, Panagos et al., (2024), 19 SHIs were selected to assess and monitor the state of soil health at EU level. These selected SHIs, grouped under different categories, represent the main soil degradation processes, with thresholds marked up for each indicator to determine if the soil can be considered healthy or unhealthy. These thresholds, outlined in **Table 1.1**, were established based on evidence from scientific literature and parameterized for each selected indicator. However, this EU-wide threshold can result in high uncertainties as well as an inaccurate assessment of soil health. Factors which cause these high uncertainties and inaccurate assessments ranges from a spatial variation of soil types, ecosystem functions and climate regions. Furthermore, the proposed 19 SHIs contained in the Mission Soil Implementation Plan cover the proposed descriptions of the Soil Monitoring Law so may be biased in not providing the full picture of an environment. Furthermore/Also, surrogate SHIs may need to be introduced to account for SHIs which cannot be easily obtained or measured (Broothaerts et al., 2024).

Table 1.1. Mapping Soil Degradation SHIs and Thresholds from Broothaerts et al., (2024) to Mission Soil Implementation Plan

Groups of soil degradation processes	Indicator	Threshold	Link to Mission Soil Indicators (see Figure 1.1)
Soil erosion	Water erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Soil structure and absence of soil sealing and erosion
	Wind erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	
	Tillage erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	
	Harvest erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	
	Post fire recovery	Recovery rate < 1	
Soil pollution	Copper excess	Cu concentration > 100 mg kg^{-1}	Presence of soil pollutants, excess nutrients and salts
	Mercury excess	Hg concentration > 0.5 mg kg^{-1}	
	Zinc excess	Zn concentration > 100 mg kg^{-1}	
	Cadmium excess	Cd concentration > 1 mg kg^{-1}	
	Arsenic excess	P (X > 45 mg kg^{-1}) > 5%	
Soil nutrients	Nitrogen surplus	Agricultural areas where N surplus > 50 kg ha^{-1} yr^{-1}	Soil nutrients and acidity; Presence of soil pollutants, excess nutrients and salts
	Phosphorus deficiency	P deficiency < 20 mg kg^{-1}	
	Phosphorus excess	P excess > 50 mg kg^{-1}	
Loss of SOC	Distance to max SOC level	Distance to max SOC level > 60%	Soil organic carbon stock
Loss of soil biodiversity	Potential threat to biological functions	≥ Moderately High level of risk	Soil biodiversity
Soil compaction	Packing density	Packing density ≥ 1.75 g cm^{-3}	Soil structure and absence of soil sealing and erosion
Salinization	Secondary salinization risk	Areas in Mediterranean region where > 30% is equipped for irrigation	Presence of soil pollutants, excess nutrients and salts
Loss of organic soils	Peatland degradation risk	Peatlands under hotspots of cropland	Soil organic carbon stock
Soil sealing	Built-up areas	No threshold applied (all built-up areas)	Soil structure and absence of soil sealing and erosion

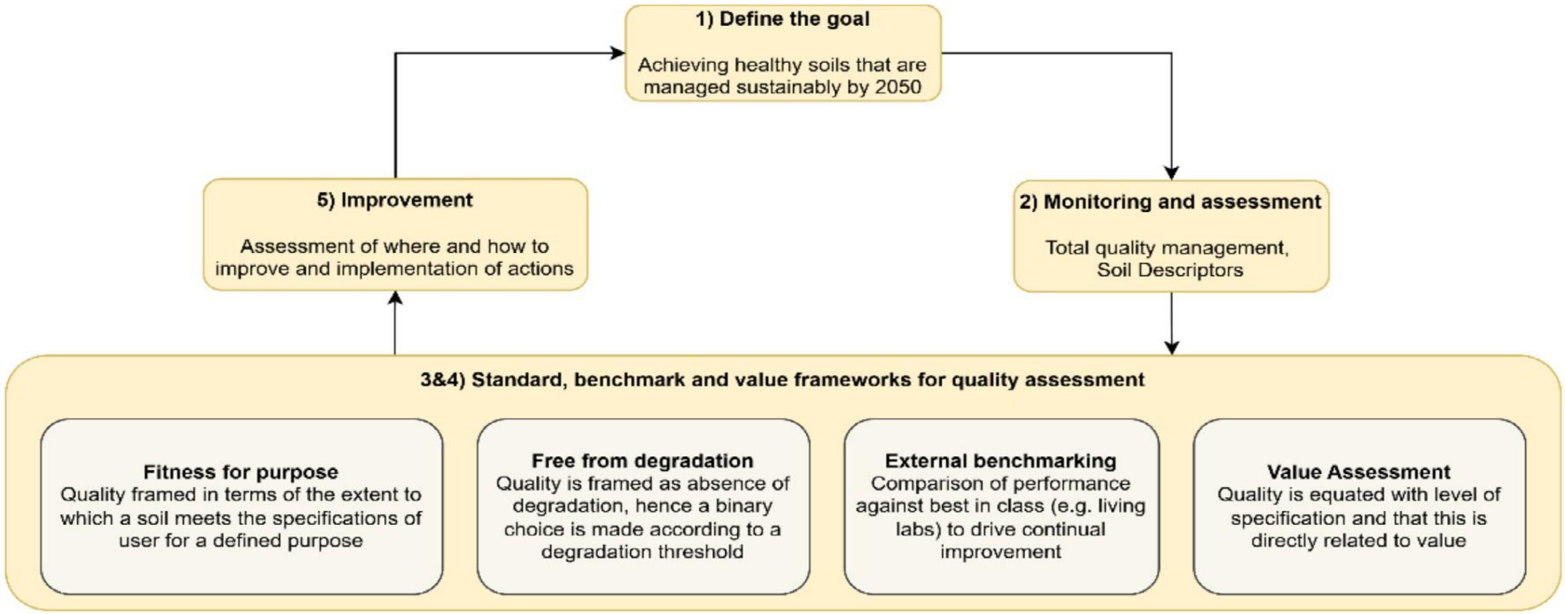
2. FRAMEWORKS FOR SOIL HEALTH INDICATOR ASSESSMENT

Soil health is a holistic description of the vitality of the soil system, especially its ecosystem and its function. Therefore, different soil characteristics will need to be quantified to provide an effective and overall assessment (Reijneveld and Oene, 2025). Selecting appropriate SHIs on the EU-scale presents significant challenges. This is due to the wide variability in climatic conditions, topography, geology, impacts and history of land use, trade-offs between ecosystems services and soil types across different regions across the continent (Bünemann et al., 2018). All these factors result in varying balances of soil processes and environmental drivers across the different pedo-climatic conditions.

SHIs can be referred to as parameters derived from physical, biological and chemical properties which describe the condition of the environment, its impact on human health, wider ecosystems and materials and their capacity to deliver vital ecosystems services or functions (Bünemann et al., 2018; Faber et al., 2022). SHIs are frequently employed on a national or field scale. On the national scale, they are used to evaluate soil functionality, inform policy development and help create effective land use management strategies whereas at the field scale, they are applied in determining suitable levels of soil nutrients and soil pH for cultivation of particular crops (Reynolds et al., 2013; Orgiazzi et al., 2017).

Therefore, the selection of these SHIs is critical as they should serve specific objective(s), notably, targeted at reflecting the condition or performance of the soil's capacity to provide specific functions or ecosystem services. Hence, these indicators play essential roles in making informed policy decisions, management practices and interventions. These issues further highlight the need for careful selection and potential aggregation of these indicators in guiding future policy decisions and improving sustainable environmental practices short and long term (Bünemann et al., 2018).

Moreover, SHIs can be viewed from the perspective of different soil quality frameworks. Adopting a different framework may alter the indicators of interest or how they are interpreted compared to other frameworks (Campbell et al., (2025). These are outlined in **Figure 2.1** below and discussed in subsequent sections.



Assessment approach	Soil quality thresholds must be defined for the function (purpose) and customer	Must define thresholds for degraded and non-degraded soils	The boundary for the upper percentile must be defined to consider best practice	Soil, soil services or functions are valued on some scale
Interpretation	Relative scale with thresholds for indicators	Binary choice with an indicator threshold to differentiate degradation	User performance compared to performance of best practice	Value assignment and cost/benefit or return on investment determined
Relativism of quality	Absolute threshold	Absolute threshold	Relative to desired outcome	Relative to value specification
Target stakeholders	Soil managers	Policy makers	Soil managers	Policy makers
Example	Cornell score card Gugino et al., (2009)	Soil degradation processes Panagos et al., (2024)	Soil health benchmarks Feeney et al., (2023)	U.N. SEEA UN et al., (2021)

Figure 2.1. The total quality management (TQM) framework for continuous improvement and various quality approaches in soil monitoring assessment and management, taken from Campbell et al., (2025).

2.1 Soil Quality in the Context of Fitness for Purpose

The quality of soil is inherently more complex than the quality of air or water because it's a multiphase living system. Soil is composed of solid, liquid and gaseous elements, is living, and can be used for different purposes (Nortcliff, 2002), ranging from supporting plant growth, regulating water flow, sequestering carbon and sustaining biodiversity. These variety of purposes require a multifaceted approach to evaluating soil health, making it even more complex.

Soil quality can be defined as "*the capacity of the soil to sustain biological process, maintain environmental quality and promotes plant and animal health within the land use and ecosystem boundaries*" (Doran and Parkin, 1994). Based on this definition, soil quality must be assessed against the intended use of the soil, in essence, ***fitness for purpose***. This is often applied at the field and farm scale where the purpose, such as growing a crop, is easily identified.

Fitness for purpose requires that soil quality must be assessed in relation to its intended use and location. This is especially evident with the increasing demand for both food and biomass-derived energy from plants due to an ever-increasing global population (Gregory and Nortcliff, 2013). In 1976, the Food and Agriculture Organization (FAO) designed the Framework for Land Evaluation which was aimed at assessing the suitability of land in relation to fitness for purpose. The inherent and manageable constraints in land suitability were considered in this assessment, and the definition of suitability are expressed in relation to the expected yields and the level of inputs required to achieve those yields (Gregory and Nortcliff, 2013).

Harvey and Green (1993) categorised fitness for purpose from two different standpoints: the customer and the wider institutional mission standpoint. The customer can be implied as the user (e.g., grower or forester in the context of soil) while the mission is regarded as the aspects of societal and public good with respect to the role of soil in providing many ecosystems services. Assessing soil quality, in the context of fitness for purpose, can also be described in a broader context accounting for different land uses and ecosystem services beyond crop cultivation and capacity of soil to sequester carbon (Harris et al., 2023).

The value of soil is best assessed as its fitness for a particular purpose or utility (Whitmore et al., 2021). Therefore, it is necessary to establish clear identification of the particular purpose, and the stakeholders that this particular purpose is relevant to also needs to be specified. In addition, it is important to establish the criteria by which fitness is assessed. Previous quality frameworks, such as the Cornell Comprehensive Assessment of Soil Health (CASH) framework (Norris et al., 2020) was focused principally on food production, indicating the farmers' perspective on soil functionality. In quantifying the fitness for purpose, scores between 0 and 100 is assigned to soil based on indicators categorised into three groups. These categories include: '*More is better*', '*Optimum curve*' and '*Less is better*' (Svoray et al., 2015).

2.2 Soil quality in the context of Free from Degradation

Many soils lack the full capacity to fulfil their potential. This is because many soils are degraded and as a result, there is a significant reduction in the capacity of soils to provide appropriate and vital ecosystems functions and services (EC, 2020). Soil degradation refers to a marked decline in soil quality or health, which in turn impairs the functioning of ecosystems. To ensure that soil can fully deliver essential ecosystem functions and services, it is crucial to minimize or eliminate severe degradation (FAO, ITPS, 2015). It affects not just soil properties but also soil functionality, soil landscape and capacity of the soil to provide ecological services thereby resulting in wider economic impacts (Buckingham and Baggaley, 2025).

The quality of soil, defined as the ability of soil to sustain its function, can be measured using SHIs; observed and evaluated soil properties that reflect the extent to which the soil provides its expected ecosystem functions and services required for the overall wellbeing of human, crops and livestock (EC, 2020). The overall wellbeing of human health, crops and livestock, collectively referred to as endpoints, is significant in assessing the functions of soil. Specific indicators, distinguished by thresholds are vital in assessing the impact of soil degradation on these endpoints as they could result in incomplete delivery of ecosystem functions. These thresholds, which could be defined as the specific limits in the environmental media of consideration are required to understand the degree of soil degradation (Lynden et al., 2004).

Soil quality in this context is currently evaluated as a binary condition by the European Union Soil Observatory (EUSO) meaning that a soil is either degraded or not with respect to specific threshold for soil threats (Broothaerts et al., 2024). In essence, the soil's quality is assessed as acceptable and does not require implementation of bioremediation strategies if it remains within the tolerable degradation levels. This approach is suitable for large scales, where broad biogeochemical or physical constraints can be identified, however, this approach is limited because it does not provide a means of assessing optimal soil quality, nor the degree of overall soil health. Hence, the threat-based approach which evaluates the effects of large-scale drivers and pressures on soil conditions aligns with the EU's operational concepts. This approach is relevant in developing policy responses targeted at identifying areas for restoring soil quality or health and reducing soil degradation to acceptable levels. Loss of soil organic matter (SOM), acidity or alkalinity, erosion and salinization are some of the soil degradation threats which can significantly impact the capacity of the soil to provide important ecosystem services and functions with the physical, chemical and biological parameters of the soil being adversely affected by these and other critical factors (Shokri et al., 2024).

Another way of framing this threats-based approach is considering it a 'zero defects' quality approach; a preventive strategy which considers the importance of maintaining baseline soil health through eliminating or minimising soil degradation threats such as loss of SOM, pollution, compaction and erosion (Blum, 2004). This approach describes soil quality by meeting minimum required standards, which represent the thresholds in the soil monitoring law, described earlier (Table 1.1). This is in contrast with the previously described quality framework 'fit for purpose'. Moreover, this approach aligns with the EU Soil Protection framework that defines soil quality as the absence of significant anthropogenic degradation such as erosion and contamination (Campbell et al., 2025).

To apply the conceptual framework for soil degradation (**Figure 2.2**) to nutrient loss and physical degradation processes such as erosion and compaction, it is essential to understand how soil responds to external pressures. This involves examining the relationship between measurable soil parameters and the critical thresholds that define degradation endpoints. Models that have the potentials to simulate how soil behaves under stress are used to effectively understand this process. These models are significant in identifying thresholds or critical limits that if exceeded, may impact water quality and human health. Converting these endpoints into equivalent values in soil (known as screening values) is important. When measurement of soil key parameters exceeds these screening values, then there is a need for immediate action to eliminate or reduce the application of harmful inputs to the soil, implementation of bioremediation strategies and mitigation measures to reduce the impact of these pressures (Baritz et al., 2021).

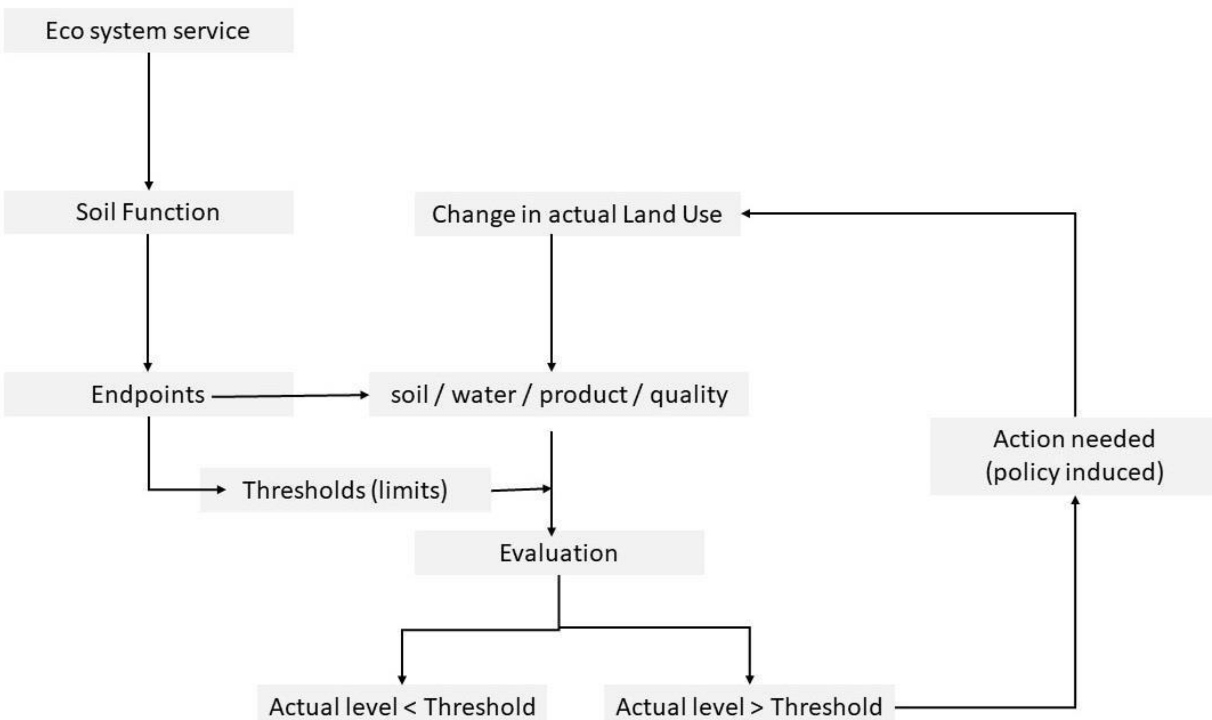
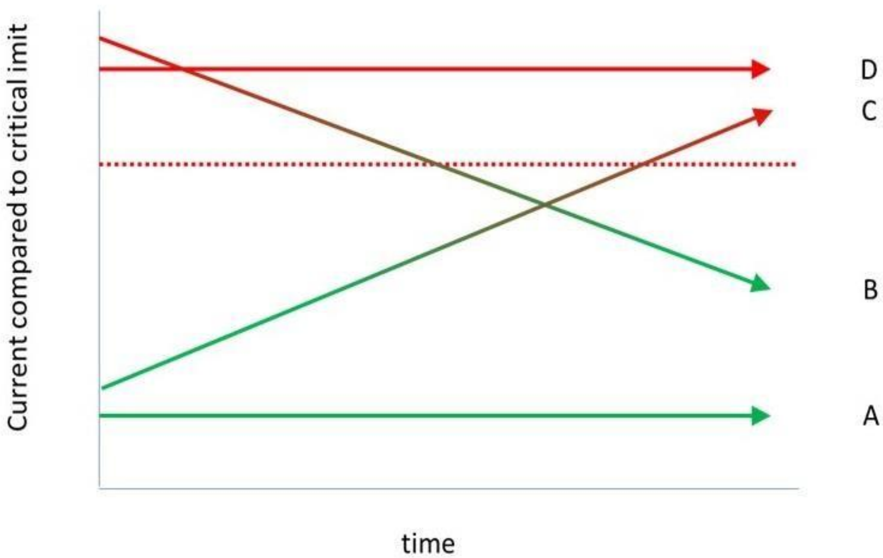


Figure 2.2. Conceptual framework for soil degradation assessment. Taken from Baritz et al., (2021)

The degree of soil degradation can be quantified at the field or national level as the extent to which the current soil condition is impacted from where a specific threshold has been exceeded in view of functions (Vegter et al., 2003). This can be demonstrated through the accumulation of heavy metals in soil. Accumulation of these heavy metals in the soil can be considered as equivalent to degradation if this results in critical limits being exceeded in relevant endpoints. This highlights the requirement to ensure that the concentration of unwanted substances in the soil does not exceed the thresholds for relevant endpoints. Therefore, there are four likely scenarios (A to D), illustrated in **Figure 2.3**, that can be used to distinguish the impact of soil degradation on soil functions (Baritz et al., 2021). These include:

1. ***Scenario A:*** The best outcome, indicates that there is no risk to soil at present and future conditions
2. ***Scenario B***: Reflects current risk conditions but no risk in the future
3. ***Scenario C:*** Indicates no risk currently but warns of potential future risk as the thresholds will be exceeded at some point
4. ***Scenario D:*** Contrary to scenario A and indicates that the condition of the soil is at risk now and in the future.



	current	future
Scenario D	risk	risk
Scenario C	no risk	risk
....	threshold	
Scenario B	risk	no risk
Scenario A	no risk	no risk

Figure 2.3. Dynamic assessment of soil degradation. Each of the 4 scenarios is represented by red and green colours, highlighted A-D. Dotted lines represent the relevant threshold in view of the specific soil function. Source: (Baritz et al., 2021).

Generally, soil degradation cannot be assessed using one single set of parameters as different soil functions have specific endpoints which require a definite assessment. In linking these connections, soil indicators such as soil pH, SOM or texture can be integrated into risk-based models which align with the current condition of the soil to specific functional thresholds or environmental parameters. Therefore, it is important to consider regional environmental conditions such as climate, crop type and general soil parameters (SHIs) in soil degradation assessment. These indicators are associated with different functions and are used in assessing various forms of soil degradation related to many extensive soil services as illustrated in **Table 2.1**.

Table 2.1: Soil threats and their relationship with wider soil services and key societal needs, taken from (Baritz et al., 2021).

	Societal needs				
	Biomass	Water	Climate	Biodiversity	Infrastructure
Soil services	Wood and fibre production	Filtering of contaminants	Carbon storage	Habitat for plants, insects, microbes, fungi	Platform for infrastructure
Soil services	Growth of crops	Water storage			Storage of geological material
Soil Quality Indicators					
Soil Organic Carbon (SOC)	+	+	+	+	(2)
Soil nutrient status	+	indiff.	indiff.	+	indiff.
Soil acidification	-	-	(1)	-	indiff.
Soil heavy metal contamination	-	-	indiff.	-	indiff.
Soil biodiversity	+	+	+	+	indiff.
Soil erosion	-	-	-	-	indiff.
Soil compaction	-	-	-	-	indiff.
Soil sealing	-	-	-	-	+

Legend

- (green) positive impact on soil service
- (red) negative impact on soil service
- Indiff. neutral or unknown impact

(1) Soil acidification / carbon storage: fulvic acid (from acidified forest floors) enhances bleaching and nutrient loss, as well as loss of dissolved organic carbon; acidic soils favour reduced decomposition

(2) Soil organic carbon/ infrastructure: organic soils are instable as platform for infrastructure

2.3 *Soil quality in the context of Value Assessment framework*

The value assessment framework highlights the value of soil resources, often in an economic sense, focusing on goods and services that they support; however, value can be formulated in terms of intrinsic value, in that soil health has value in of itself. The green accounting framework serves a key role by highlighting the significance of natural capital stocks and the ecosystem services provided. This provides comparison between Nature-based Solutions (NbS) and the engineered alternatives, which is critical in decision-making for sustainability. It is widely recognised across the EU that preservation of natural capital is significant to the economic activity and well-being of humans (Campbell et al., 2025).

To better understand the value of soil, it is important to understand the difference between ecosystem services and ecosystem functions. Ecosystem services can be defined as the beneficial flows that arise from the natural capital stocks and can satisfy human needs. They are not static but as flows or quantities delivered per unit time in contrast to stocks which describe the total amount of resources. Ecosystem functions are defined as the capacity of natural processes and components to provide products and services which can directly or indirectly satisfy human needs. There are different specific services provided by natural systems that support economic activity and human welfare. These roles or services are classified into four categories: provisioning, regulating, cultural and supporting services (Dominati et al., 2010).

The well-being of humans is directly affected by the first three categories while the supporting services are critical in maintaining these services. Dominati et al., (2014) applied this framework in quantifying the economic valuation of the roles of soils in providing fourteen ecosystem services as described in **Table 2.2** These ecosystem services are categorised as provisioning, regulating and cultural services. However, there is a need to further develop the Value Assessment, as suggested by Campbell et al., (2025) and highlighted by Obst et al., (2016). The existing soil ecosystem services framework does not adequately represent the function of soils in providing ecosystem, therefore, the significant variability among soils in their capacity to support these services is unclear. This was demonstrated by the lack of clarity on the specific roles played by soils in delivering ecosystem services although soils and soil formations are significant in regulating ecosystem services such as erosion control, water purification and waste treatment (Dominati et al., 2010).

Table 2.2. Soil ecosystem services, taken from: Dominati et al., (2014).

Types of service	Definition	
Provisioning	Food, wood and fibre	Soils physically support plants and supply them with nutrients and water. By enabling plants to grow, soil enables humans to use plants for a diversity of purposes.
	Raw materials	Soils can be a source of raw materials (peat, clay), but renewability of these stocks is questionable.
	Support for humans	Soil represents the physical base on which human infrastructures and animals (e.g. livestock) stand
Regulating	Flood mitigation	Soil has the capacity to store and retain water, thereby mitigating flooding.
	Nutrients and contaminants	Soil can absorb and retain nutrients (N, P) and contaminants (*E. coli*, pesticides) and avoid their release in water bodies.
	Carbon storage and greenhouse gases	Soils could store C and regulate their production of greenhouse gases such as nitrous oxide and methane
	Detoxification and the recycling of wastes	Soil can absorb (physically) or destroy harmful compounds. Soil biota degrades and decomposes organic compounds thereby recycling wastes.
	Pests and diseases populations	The nature of the habitat provided by soils controls the proliferation of pests (crops, animals or humans) and harmful disease vectors (viruses, bacteria) and regulates beneficial species populations.
Cultural	Recreation	The use of natural and cultivated landscapes for pleasure and relaxation (e.g. walking, angling, mountain biking)

	Aesthetics	Appreciation of the beauty of natural and cultivated landscapes (e.g. wildlife viewing, scenic driving)
	Heritage values	Memories in the landscape from past cultural ties (e.g. landscape associated with an important event of regional or national significance)
	Cultural identity	Cultural linkage between humans and their environment (e.g. valuing conservation of native species)

2.4. Soil quality in the context of External benchmarking

Benchmarks are indirect indicators of soil health derived from representative datasets that represent a statistical sample of soils from a region or nation against which local samples can be compared. Therefore, they do not indicate direct evaluation of specific soil functions as they are more reflective of the overall conditions of a location compared to the distribution, often for a given land use, than the performance of each specific soil function. These benchmarks are useful to farmers and landowners in comparing their measured SHIs against expected ranges (Feeney et al., 2023). They are applicable to different contexts, at national and multinational levels, in establishing external benchmarks. Within a total quality framework, they provide a lens for users to understand how they compare with others and potential achievable improvement. This helps to provide a platform for management objectives based on the success of other parameters in similar contexts (Feeney et al., 2025).

Initially benchmarking was associated with targets or threshold values which are established through either 'fixed', 'reference', 'distribution' or 'relative change' approaches. However, the external benchmarking distribution approach doesn't use targets, perse. Instead, the distribution indicates achievable levels of soil functions and are applied in assessing soil indicators and improving soil health (Feeney et al., 2023). Conversely, in the fixed approach, fixed threshold or target values are generated from direct objective observations under specific environmental conditions such as soil type and climate. This is not preferred if targets are set on means for example, as the mean of a degraded soil is still degraded. The external benchmarking approach is assessed against a population with the aim of continual improvement to attain a certain percentile within that distribution of the population. In addition, the relative change approach is defined as an increase or a decrease of a certain percentage of the current values within a specified number of years (Matson et al., 2024).

In external benchmarking, measurements collected from a particular location are compared to similar measurements from equivalent soils relative to similar land use and management practices. This approach allows landowners and farm managers to evaluate the conditions of their soils within a wider perspective, thereby establishing the range of their soils (at the lower or upper end of the desirable range) (Campbell et al., 2025). External benchmarking contradicts establishing indicative threshold within a particular population with the aim of supporting one or more targets to be derived from the mean, median or other percentiles of a distribution (Feeney et al., 2025). This framework allows soil managers to establish realistic goals within continual improvement which are beneficial in implementing restorative strategies if the condition of their soils fall below the lower end of a desirable range. External benchmarking operates on the principle that the goals are achievable based on the evidence that they have been successfully attained by others operating under similar environmental conditions (Campbell et al., 2025).

In addition, the external benchmarking framework is useful as a consistent support mechanism in establishing a quality-centred approach that will be commonly adopted by farmers and landowners. This will enable soil managers to evaluate indicators of soil functions against similar indicators established by other soil managers operating under similar soil types and land use types. Results have been obtained by applying this framework as demonstrated by Soil Fundamentals (SOD) (2024) and Feeney et al., (2023, 2024) and illustrated in **Figure 2.4**. As shown, the measurements collected by the soil manager for a farm field, represented by the blue line, were observed to fall in the typical range below the upper percentile, indicating there is opportunity for improvement. As a result, the management practices on this farm field could be subjected to review. Soil managers can assess the best management practices and implement them through the evaluation of the soil indicators' performance, seeing if they can shift their position to a higher percentile, indicating improvement.

Furthermore, there are multiple approaches in conceptualizing soil quality. However, it is essential to state that no single approach should be considered the only approach as each way offers a unique perspective appropriate for purpose, scale and end user. For example, Drexler et al., (2022) reported site-specifics SOC benchmarks that enables the interpretation of measured SOC contents for German mineral soils under agricultural use based on the dataset of the first German Agricultural Soil Inventory. The most commonly used indicator of soil health is SOM or SOC (Bünemann et al., 2018). This framework established two concepts used in setting reference values for interpreting measured SOC. In the first concept, SOC thresholds are well established to provide a direct interpretative framework in evaluating soil properties relative to soil functions. In the second concept, a set of benchmarks allows the indicative comparison of SOC values with a representative dataset but no direct evaluation relative to specific soil functions are defined (Drexler et al., 2022). This concept supports farmers and extension services to assess whether their measured SOC contents are within the expected SOC median range for their sites.

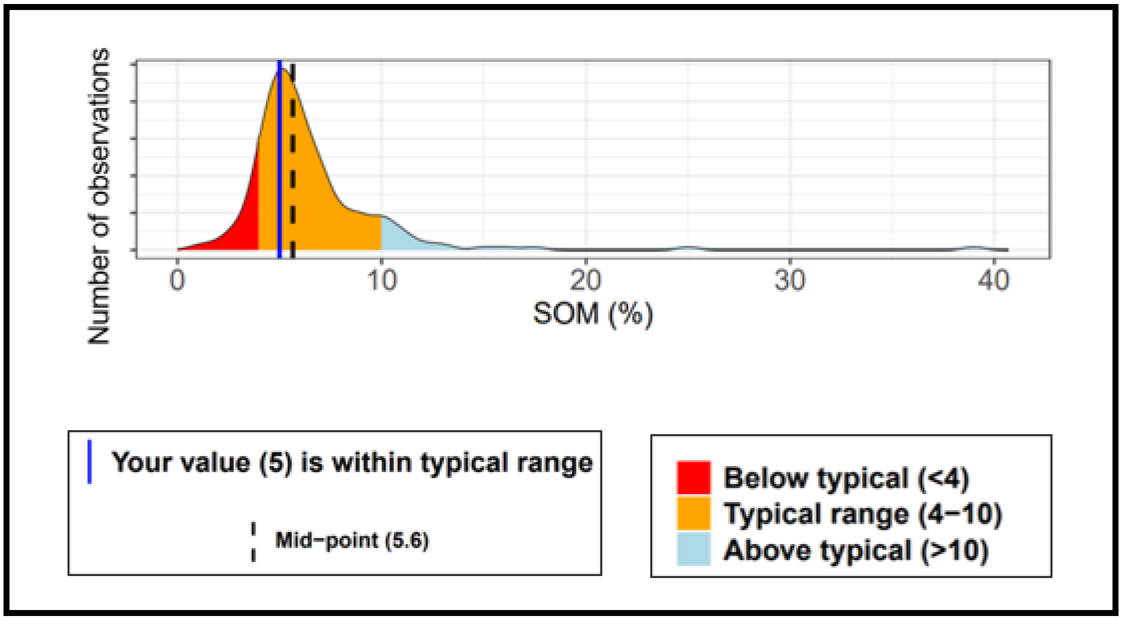


Figure 2.4. Illustration of output from the Soil Fundamentals (SOD) tool (SOD, 2024), as demonstrated in Feeney et al., (2023). This output describes the distribution of SOM with the data representing a medium loam soil under cropland management, derived from the UK Countryside Survey monitoring dataset (Robinson et al., 2024). In the graph, the blue vertical line marks a value of 5, which falls within the typical range. The black dotted line indicates the mid-point value of 5.6. The red section of the curve shows SOM levels below the typical range, the orange section represents the typical range, and the light blue section indicates values above typical, based on the data collected to date.

3. CRITERIA FOR SOIL HEALTH INDICATOR THRESHOLDS

Soil health and the capacity of the soil to provide expected ecosystem functions and services are assessed and quantified using SHIs. Thresholds can be applied in evaluating these by determining the acceptable levels of soil functions. These thresholds account for a range of external factors including soil, climate, land use, management and overall land use and environmental history. Therefore, there is a need to establish reliable frameworks or criteria in selecting these indicators. There are four approaches in setting thresholds for soil indicators. These include 'fixed', 'reference', 'distribution' and 'relative change' frameworks (Matson et al., 2024) as described in **Figure 3.1** below. These are also described in subsequent sections of this report.

3.1 *Fixed approach*

The fixed approach is the most commonly used criteria in establishing thresholds for SHIs. In this approach, fixed value thresholds are established from direct and objective observations under specific soil conditions such as soil type, climate and geology and also from the most relevant and available literature. This approach involves setting thresholds for specific trace elements to avoid overaccumulation of these elements in the soil which could be harmful on soil biota. This method of threshold setting for soil indicator establishes a direct correlation between a particular soil function and indicator value (Matson et al., 2024).

In addition, the fixed approach may also be applied in setting appropriate targets for degraded soil requiring intervention. Soil erosion constitutes significant threats to soils in the EU and impacts severely on ecosystem functions and services, with reported mean soil loss rate of 2.46 t/ha/yr and annual soil loss of 970 Mt (Panagos et al., 2015). An erosion threshold of 2 t/ha/yr was proposed by Panagos et al., (2015) for future soil protection measures focusing on 24% of European lands at greatest risk of degradation. This was assessed to be appropriate for healthy soils by the Soil Monitoring Directive (EC, 2023). Also, values considered to be realistic and reasonable based on previous practical observations could also be set for SHIs in fixed approach. For example, an upper threshold of 1-t/ha/yr could be set for eroded soil based on the evaluation of tolerant level of soil erosion if less than 1 or equal to the rate of soil formation (Soine et al., 2016).

The fixed approach of setting thresholds for SHIs, although serves as a quick method of initiating assessment at a large scale, and can be applied at field level, has limitations. There is lack of clarity or information on the scale required to effectively stratify the fit-for purpose thresholds by climate, soil, land use, management, history and other context-specific requirements (EEA, 2023).

3.2 *Reference approach*

The reference approach allows particular SHIs data to be compared to a reference region where the soil functions and ecosystems services of top priority are optimal and desirable. In this approach, the assigned static values are expressed as a percentage, representing the condition of the soil relative to a reference scenario in which soil process functions optimally. The values can be stratified as required to reflect different land use, soil types and management practices (Matson et al., 2024). They are designed based on the understanding that natural vegetation soils such as grassland are in better quality and support ecosystems functions such as nutrient cycling, biodiversity, water infiltration, carbon content more effectively compared to well cultivated land (Das and Maharjan et al., 2022; Maharjan et al., 2020). This implies less undisturbed and uncultivated land such as pasture have the potential to support soil processes with maximum impact for agricultural soils. However, in this approach of setting threshold for SHIs, there is a requirement for the selection of suitable areas or conditions that will serve as a benchmark. This must be applicable to scenarios where the soil shows significant and attainable values for the indicator as compared to an agricultural soil (Matson et al., 2024). Thus, there is a strong possibility that many regions or indicators will not have suitable reference points.

3.3 *Distribution approach*

While the distribution approach has been used in the past to set thresholds or scoring (in USA (Nunes et al., 2024) and France (Chen et al., 2019)) (Matson et al., 2024), it is not something we advocate. The reason being that setting an objective to the mean of a degraded soil is not helpful. Instead, external benchmarking, as described previously uses a distribution as a kind of ranking mechanisms, so a grower can see where they sit in a distribution of a property for soils under similar land use and practice. It provides a lens through which growers can develop goals to incorporate practices leading to continual improvement. Comparison through a distribution offers the advantage that a grower can see that better performance is often achievable.

External benchmarking of this type, without thresholds, was proposed by (Feeney et al., 2023) in the United Kingdom (UK) based on soil type and climate. Feeney et al. (2023) demonstrated the use of this approach by users of multi-indicator webtool to identify the position of their data within a population of soils within the same land use type in the UK. The multi-indicator webtool screens important soil indicators such as pH, SOM, bulk density and the abundance of earthworms contained in soils. They suggested that this approach can be applied in continual improvement of soil, providing a lens through which stakeholders can compare their performance to similar land uses on similar soils.

The distribution approach with thresholds is generally undesirable. This is because the distribution will be unrepresentative of soil functional capacity if the soil area is already degraded. Hence, the external benchmarking approach (Feeney et al. 2023) is more desirable as it aids goal setting to attainable objectives by moving up the distribution.

3.4 *Relative change approach*

The relative change approach requires setting SHI thresholds based on the local conditions of the soil. In this scenario, the threshold is specified as an increase or decrease of a particular percentage within a defined timeframe. The principle behind this approach is that setting thresholds is required to facilitate soil health improvement, irrespective of the difference between the current and potential thresholds values. Hence, the threshold value is only fixed for a limited number of years after which the soil is re-evaluated and change in threshold values is initiated (Matson et al., 2024). This approach allows users to apply it at the local and regional scales as well as to provide an evaluation of trends due to being highly specific to situations and takes the starting point into consideration. Minasny et al., (2017) reported that the ***"4 per mille initiative***" introduced at 2015 United Nations Climate Change Conference (UN COP21) aimed at improving soil health and enhance climate change mitigation as an example of relative change approach applied at a local scale. In 2020, it was found that between 60-70% of the soil in Europe was reported to be unhealthy (Veerman et al., 2020). To improve this figure, the European Commission adopted the relative change approach on a larger scale and establish a threshold of 75% of healthy soils by 2030 indicating a 100% relative change from the baseline (Veerman et al., 2020). This approach is seen to be simple to adopt with no requirements for extensive knowledge and large data sets of reference situations. However, its limitations are that it has no defined end point, and the approach is unable to indicate whether soil health status is good enough or not. Moreover, in the case of high uncertainty with relative change, it may not be appropriate for mapping, and a robust monitoring network might be required before it is applied at the regional level (Matson et al., 2024).

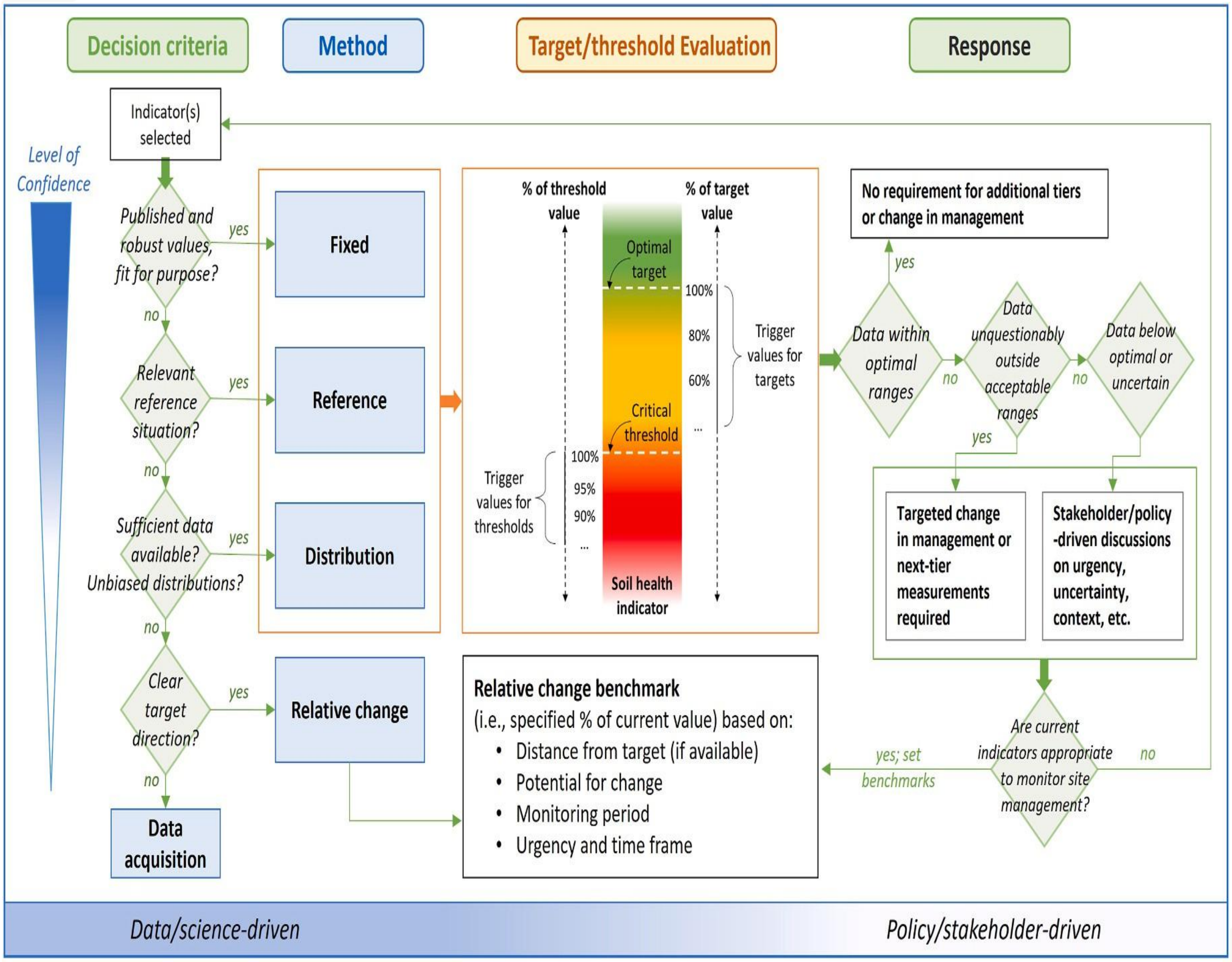


Figure. 3.1. A framework for the selection and the use of targets and thresholds for SHIs. The decision tree flowchart first supports the selection of an approach to set targets or thresholds, followed by a method to normalize across different indicators through '*trigger values,*' percentiles that indicate how far soil data is from the target or threshold. Based on trigger values, the decision tree flowchart supports responses in management or further data collection. Source: (Matson et al., 2024).

4. INDICATOR SELECTION WITHIN NATIONAL MONITORING SCHEMES

Soil plays significant roles in our communities, environment and economy by contributing to climate regulation, food security, forestry and biodiversity (Buckingham and Baggaley, 2025). Soil Monitoring refers to the use of SHIs to convey meaningful information about the progress of a project or sampling campaign. It is an important feedback mechanism relevant in evaluating whether objectives are being met and helps to guide current and future decision making (Rey et al., 2022). Results from monitoring campaigns are of high significance value because they form the background required in conservation planning and modelling of potential environmental changes (Bakhmet et al., 2022).

A Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law, SML), was proposed by the European Commission with the aim of establishing a soil monitoring framework and assessing soils throughout the EU. This is part of the long-term objective of the EU to achieve healthy soils by 2050 (Robinson et al., 2024). Reijneveld and Oene (2025) also highlighted that the importance of soil health assessment should be recognized by government, and as a result, many government agencies across different countries globally recently established soil monitoring programs. This is because of the importance of soil health in achieving wider SDGs such as zero hunger (SDG 2), good health wellbeing (SDG 3), clean water and sanitization (SDG 6), sustainable consumption and production (SDG 12), climate action (SDG 13) and life on the land (SDG 15).

In the UK, they have several years of experience in developing and refining range of soil monitoring programs as they advance their -term soil monitoring initiatives. This is because these soil monitoring programs provide evidence of success in policy making while continuing to identify areas that require further action. They provide assessment to soil protection and restoration and justification to monitor the conditions of the soil (Buckingham and Baggaley, 2025).

Over the last half century, important lessons have emerged from the UK's soil monitoring programs which may contribute to the effort of the EU in designing similar sampling campaigns. These lessons include:

a. Adopting a question-based approach to facilitate monitoring activities. These need to be driven by clear scientific and policy-relevant objectives.
b. Establishing a clear and robust statistical design for the purpose of soil monitoring.
c. Selecting SHIs that are relatable to both policy needs and underlying scientific questions.
d. Ensuring SHIs can evaluate changes over time using well-tested methodologies applicable to both soil types and land uses.
e. Maintaining long-term validity that supports sustained monitoring efforts that inform strategic decision-making and adaptive policy development (Robinson et al., 2024).

Currently, there are soil monitoring programs in the UK developed with the intention of achieving similar outcomes set by the EU programs. These monitoring programs, actively engaged in collecting data across the UK based on stratified random design as the best preferred methodology in the impact assessment for the Soil Monitoring Law, are described in **Table 4.1** below:

Table 4.1: Known UK-based soil monitoring programmes

Monitoring Program	Country	Established	End Date
Countryside Survey	Great Britain (GB), Northern Ireland (NI)	1978 (GB), 1986 (NI)	Ongoing
Environmental and Rural Affairs Monitoring and Modelling Programme (ERAMMP)	Wales	2023	Ongoing
Ecosystem Survey (EES)	England	2023	Ongoing

The UK monitoring programs were developed in response to the same fundamental objectives as the proposed EU initiative; to understand the state and dynamics of the environment under the influence of anthropogenic drivers and land management pressures. Furthermore, soil monitoring programs are critical to identifying areas where the intervention is necessary. Therefore, these monitoring programs are specifically tailored within administrative boundaries in line with the jurisdiction of authorities in need of performance monitoring and capacity to implement sustainable land management practices including soil conservation measures (Robinson et al., 2024).

Although monitoring of soil health in the face of climate change is a top priority for the Scottish Government (Neilson et al., 2021), however, the Environmental Standards Scotland report (2024) highlighted that Scotland do not have a comprehensive soil monitoring program as reported in other parts of UK , and this has resulted in lack of adequate information on whether the number and severity of soil erosion in this region is increasing or decreasing. Robinson et al., (2024) reported that Scotland is developing a new soil monitoring scheme with due consideration of its unique soil types, land uses and climate conditions. Currently, Scottish Soil Monitoring Framework (SSMF), based on justification from the Strategic Research Program (2022-2027), was set up to support the objectives of the Scottish Biodiversity Strategy in assessing changes in soil health, thereby providing robust evidence in tracking and validating environmental impacts and evidence-based decision making. This framework was set up with clear vision, purpose and objectives in ensuring that the soil monitoring programmes are transparent, robust, fit for purpose and can be interpreted by wide-ranging audience (Buckingham and Baggaley, 2025).

It is important to know that these UK monitoring programs are developed with a set of guiding principles. These set of principles of designs extracted from five decades of practical experience and implementation of soil monitoring are significant in helping the EU achieve set target of healthy soils by 2050. They were applied widely in UK monitoring programs as described below and can also be used to help future soil monitoring programs (Wilkinson et al., 2016).

4.1. Principles of Purpose within the National Monitoring Schemes

The principle of purpose clearly establishes the aim of the monitoring program and relevant questions it addresses. Soil monitoring programs were aimed at assessing environmental changes over time in response to both natural and human influences to provide policy advice. However, this has evolved with time with more specific objectives (Robinson et al., 2024). Currently, the purpose of soil monitoring programs such as ERAMMP in the UK is to collect data across different land uses and management, evaluate changes and future impact using models. By doing this, evidence is provided on future needs to establish effective policies for socio-economic and environmental benefits (Robinson et al., 2024). Soil monitoring programmes need to be fit for purpose (Buckingham and Baggaley, 2025).

To achieve this purpose, three important factors need to be considered. Firstly, it is important to consider the environmental drivers and pressures, spatial and temporal scales and variability when designing sampling intensity or frequency. The frequency which the survey or design is conducted is based on the time required for changes or impacts to be observed. Thus, selecting adequate soil indicators that align with the mission of monitoring and type of impact is key to effective soil monitoring (Bakhmet et al., 2022). Secondly, there is a need to consider the long-term impact of selected SHIs or intervention strategies to ensure historical continuity, especially with the advancement of technology over the next 40-50 years. For example, Bentley et al., (2024) reported that sustainable land management was promoted as an intervention mechanism to stabilize and reverse the loss of SOM from cropland which contributes to climate change compromising soil health and ecosystem balance. However, there was no evidence of positive impacts on scale. The first signs of impact of reversal of soil carbon loss were reported using 40+ years of national soil monitoring from the Countryside Survey.

Finally, although the principle of purpose is to ensure it addresses relevant questions, it should be flexible enough to respond to new and emerging issues or questions (Robinson et al., 2024). It is important to consider the effectiveness of any soil monitoring program to define in advance the extent to which it can generate meaningful information about how soil indicators change over time. The flexibility of soil monitoring is crucial in creating awareness on the role and significance of soil in our society and in engaging wider audiences (Aalders et al., 2009).

4.2. Adaptability and flexibility

This principle is aimed at infusing flexibility into the soil monitoring program to ensure their adaptability to evolving circumstances, reporting requirements and priorities. Because of this, the need for a periodical review and updating of SHIs and methodologies are required at appropriate intervals. This is necessitated based on evidence from the Countryside Survey where there were emerging requests from the devolved administrations in the UK on increasing the number of reporting units (Emmett et al., 2010; Reynolds et al., 2013). Soil monitoring programs need to measure and assess soil health baseline status and changes in soil over time (Reijneveld and Oene, 2025).

The importance of reviewing and updating indicators and methodologies can be justified based on experience from the Countryside Survey rolling program design where some indicators are measured now every year on a 5-year cycle, while other indicators are measured once every 10 or more years depending on need (Robinson et al., 2024). Bakhmet et al., (2022) reported that soil monitoring is carried out at present time intervals. For example, the analysis of microbial community in undisturbed soils is done every 2 years while the status of the humus soil is performed once every 5-7 years. However, they suggested an increase in the sampling frequency to ensure significant human impact. In designing any soil-monitoring programs, it is important to consider that current issues and risks of concern may not be issues and risks in the future. This is based on the uncertainties surrounding prediction of changes in climate (Aalders et al., 2009).

4.3. *Accessibility and transparency*

This principle ensures that soil monitoring data, data collection methods and mechanisms of reporting are accessible to relevant stakeholders and transparent in the monitoring process (Robinson et al., 2024). Soil monitoring programs are crucial in climate change mitigation and as a result, it is important to establish accessibility and transparency in the monitoring protocol. When setting up soil monitoring programs, it is important to ensure that these programs are transparent, robust and can be interpreted by wide-ranging audiences (Buckingham and Baggaley, 2025). Although EU Member States have flexibility in setting up targets, defining scope of land sector and soil monitoring programs, they are required to conduct this in a transparent manner with sufficient accuracy, consistency and compatibility (Böttcher et al., 2025).

Böttcher et al., (2025) suggested that transparency can be improved by applying open-source data collection, focusing on essential elements such as clarity, precision, accuracy, participation, equity and system compatibility. There is also a need to adopt a unified monitoring system which combines frequent and alert-driven soil monitoring with regular data collection. In addition, Reijneveld and Oene, (2025) highlighted that a universal soil health monitoring report would be beneficial to relevant stakeholders, government agencies across different countries in EU to understand and communicate effectively.

Similar approaches were adopted by the UK monitoring designs as reported by Black et al., (2008). They reported that these monitoring designs, method of data collection and procedures are open and well documented followed by a rigorous transparent process. In addition, the R_Core_Team (2021) demonstrated that the use of standardized data procedure and quality assurance scripts in a programming language is important in keeping records of data, ensuring efficiency and robustness with due diligence given to data preservation, for future purposes.

To further ensure transparency and accessibility, all locations during the process of data collection are preserved and documented with high level of confidentiality. The essence of this is to preserve the scientific integrity of the monitoring program. There is possibility of landowners engaging in practices that could alter the result of the survey with prior knowledge of the locations and results. Secondly, this helps in preventing putting undue pressure on the landowners from responding to requests from researchers and other stakeholders aiming to conduct experiments at same locations (Robinson et al., 2024).

4.4. Ethical considerations

In developing soil monitoring programs, ethical considerations are of high priority. Soil monitoring programs need to be carried out with the consent and permission of the landowners. This procedure involves contacting the landowners before visiting to get their approval. Robinson et al., (2024) reported the successful implementation of this procedure with more than 90% of landowners giving their consent.

4.5. Timeliness

Timeliness is of utmost importance in soil monitoring design. The period required for the completion of the process, decision making and potential interventions where necessary need to be considered and documented. Also, the expectations of the stakeholders with respect to frequency of the reporting need to be considered to ensure there is a balance between scientific requirements with communication demands (Robinson et al., 2024). Changes in soil occur over time (Reijneveld and Oene, 2025), therefore, there is need to monitor the impact of human activity on soil which can be assessed on short time (months), medium (years) and long-term (decades) time scales (Robinson et al 2024). Estimating changes in SOC stocks and monitoring these changes within a particular area of interest over time is one of the important components of the Integrated Carbon Observation System (ICOS), a pan-European long-term research infrastructure (Arrouays et al., 2018).

5. SAMPLING DESIGN

Sampling design can be defined as the selection of the most appropriate method of sample selection used in estimating the properties or features of a population. It describes the selection of defined elements from a population and how these sampled elements form the sample population (Carter and Gregorich, 2007). Soil sampling is challenging because of the large variability in soil. It involves a two-step process of soil collection and processing (Pal, 2013).

5.1 *Design and Stratification*

Soil benchmarks are developed from subsets of larger datasets which allows for an indicative comparison with regionally representative measured values (Feeney et al., 2023). Accurate reporting of both the current and temporal changes in environmental variables, required in addressing relevant questions in policy making, demands a robust and structural design. This principle has been segregated into four themes in the UK Countryside Survey:

A. Stratified random sampling approach
B. Selection of appropriate strata for monitoring
C. Identification of meaningful indictors (sample size)
D. Definition of suitable reporting units

5.1.1. Stratified random sampling approach

This approach involves partitioning a population into smaller groups known as strata (Wu et al., 2024). Consistent stratification of land into relatively homogeneous strata is an essential spatial framework for the comparison and analysis of soil and environmental data across large heterogeneous sample size allocations (Metzger et al., 2013). It ensures more efficient collection of data compared to simple random sampling and results are generated by strata. As a result, this helps in improving the precision of estimated outputs (Liu and Pontius, 2021). Stratified random sampling has many advantages. It ensures flexibility in selectively highlighting some strata over others by adjusting sample size allocations.

Also, this approach is versatile. It does not only allow the estimation of aggregates such as means and totals at the population level but also can be used in addressing queries from subsets of the population defined by selection criteria during the time of analysis (Nguyen et al., 2021). In addition, stratified random sampling allows adequate coverage of smaller groups and allocation of different resources across the different smaller groups (Robinson et al., 2024). Results can also be scaled up in this approach, while accounting for observed variability and the capacity to make comparisons with like –for-like across administrative boundaries, if required (Robinson et al., 2024). Factors such as soil type, topography, climate and vegetation with the potentials of influencing SOC spatial and temporal distributions should be considered as well in stratified random sampling (Vanguelova et al., 2016).

5.1.2. Selection of appropriate strata for monitoring

The UK Countryside survey was designed based on the demand for policy making that depends on reliable statistical estimates of soil indicators, reflecting both the current status and the changes in environmental features across the countryside. A robust statistical sampling design that provides reliable representation of the diverse range of environments is needed to achieve this purpose (Metzger et al., 2013). It is important to define sampling strata when selecting them . This provides the flexibility in choosing the number of strata that ensures resulting samples meets the targeted levels of precision and reporting requirements. Selecting the optimal strata number of strata indicates a balance between statistical precisions and complexity, which is challenging in agricultural contexts due to uncertainty about the suitability of spatial datasets for stratification (Lawrence et al., 2020). Strata should reflect essential sources of variation relevant to soil properties within the monitored system, not confined by administrative boundaries and must be stable over the years to allow long-term monitoring and comparison (Robinson et al., 2024).

5.1.3. Sample size

Creating appropriate sample sizes are an important step in designing and implementing soil monitoring programs. It involves selecting the required number of samples needed to provide statistical validity and influence for hypothesis testing (Lakens, 2022; Robinson et al., 2024). When justifying sample sizes, it is important to assess which effect sizes are of interest and how the collected data can inform inferences about the sample sizes. The smallest effect size of interest, minimal effect size that would be statistically significant and what effect sizes are expected and the basis for these expectations need to be factored when justifying sample sizes (Lakens, 2022). The number of samples to be collected in relation to soil indicator threshold and expected level of change over time can be determined using power analysis (Robinson et al., 2024) as demonstrated by Black et al., (2008) in designing the UK Soil Monitoring programme.

5.1.4. Definition of suitable reporting units

Appropriate and suitable reporting units in soil monitoring programs are an important aspect of quality assurance for all researchers to ensure that their research can be compare and replicated across the world (Both et al., 2015). Analysis of results can be conducted across multiple reporting units if there is adequate representation in the sample and the relationship between the sampling structure and each reporting is well documented (Robinson et al., 2024).

5.2 INDICATOR SELECTION

At an EU Mission indicator cluster training meeting (NEIKER, Vitoria, Spain, September 2025) organized by the AI4SH project and delivered with Soil Health Benchmarks project, the prioritization of indicators was discussed. The discussion led to three groups of indicators being identified. High priority general indicators, almost always useful in assessing soil; indicators that are general but for more specific threat-based purposes and bespoke indicators targeted at specific soil quality or health issues that might need to be addressed. Table 5.1 provides a broad overview of the indicator grouping following the assessment.

Table 5.1. Workshop grouping of indicators based on general priority and scale specificity. Some metrics like pH and EC are measured together in the lab and are thus included together.

Group	Indicators
High priority general	pH (EC) SOM SOC (N) Bulk density
Specific threat-based sets of indicators	Nutrients Inorganic pollutants Organic pollutants Erosion Biodiversity
Location or issue specific	This might be specific organisms, pathogens, or pollutants for example, generally confined to the local scale.

5.3 CRITERIA FOR INDICATOR SELECTION

Due consideration in the selection of well-defined and scientifically robust indicators is important to ensure that the selected indicators are relevant to both the ecological processes and overarching functions they are intended to represent. Also, they must be applicable and relevant to the specific land use, management practices and climactic conditions of the ecosystems under consideration (EEA, 2023). Indicators selection should accurately reflect the ecological processes that aligns with the delivery of the function being evaluated (Vazquez et al., 2025) because of the difficulties in measuring soil functions directly.

Robison et al., (2024) highlighted five different criteria/principles to be considered in selecting indicators for soil health monitoring thereby ensuring that the selected indicators address policy and underlying scientific questions and also detect changes. These include but not limited to, measurability of the selected indicators, sensitivity and specificity, targeted indicator selection, validity and reliability.

5.3.1 *Measurability*

In selecting indicators to assess soil health, identification of relevant indicators with the capability of measuring soil processes directly is the first step (Vazquez et al., 2025). Soil indicators must be measurable and quantifiable (Robinson et al., 2024). Soil processes are defined as series of actions that result in specific outcomes within the ecosystem. Selecting indicators based on soil processes are particularly expressed as rates, capturing the speed at which a process occurs. Therefore, measurements of these processes could be carried out in the laboratory or field. In the event when direct measurements of soil processes are not feasible, it is possible to assess the presence or abundance key biological drivers, the physical or chemical conditions of the soil that enables these processes to occur (Vazquez et al., 2025). Measurement of soil processes must also be reproducible reliably and consistently, across different land use observers or in the field or laboratory. For example, Robinson et al., (2024) highlighted that soil monitoring schemes in the UK use a 0-15 cm topsoil measurement core in collecting and processing soil samples.

With the aim of linking soil indicators and soil functions thereby supporting assessment of ecosystem services and wider policy questions (Emmett et al., 2023), the UK Soil Indicator Consortium (UKSIC) developed a set of 13 high-level soil indicators. These soil indicators as pH, SOC, bulk density, total nitrogen, Olsen phosphorus, carbon-to-nitrogen ratio, potentially mineralizable nitrogen, extractable magnesium and potassium and aqua regia extractable metals (Cu, CD, Zn and Ni) were selected based on key criteria such as relevance, sensitivity, discrimination and signal-to-noise ratio, measurability and practicality as well as efficiency and cost (Robinson et al., 2024).

In addition, Vazquez et al., (2025) reported an update on the work by Creamer et al., (2022) who developed a series of cognitive models illustrating the main biological driven processes supporting four soil functions: nutrient cycling, water regulation and filtration, carbon regulation and pest and disease management in a temperate agricultural context (**Figure 5.1**). These cognitive models identified the specific processes that support each soil function and grouped them into subfunctions. However, they did not address how biologically mediated soil processes interact with or were affected by physical and chemical conditions in the soil. As a result, Vazquez et al., (2025) developed four soil function cognitive models that integrate the chemical and physical components of the soil health with that of the biologically influenced soil processes to support sustainable agricultural production in temperate climate conditions across Europe. They also illustrate the impact of environmental conditions in these processes and describe carbon and climate regulation, nutrient cycling, water regulation and filtration and habitat provision for biodiversity. The cognitive model, developed based on the interaction between soil functions, soil processes, parameters and their associated indicators as illustrated in **Figure 5.2**, provide a robust and transparent method for SHI selection of the four functions and complete soil health assessment through a multifunctional strategy.

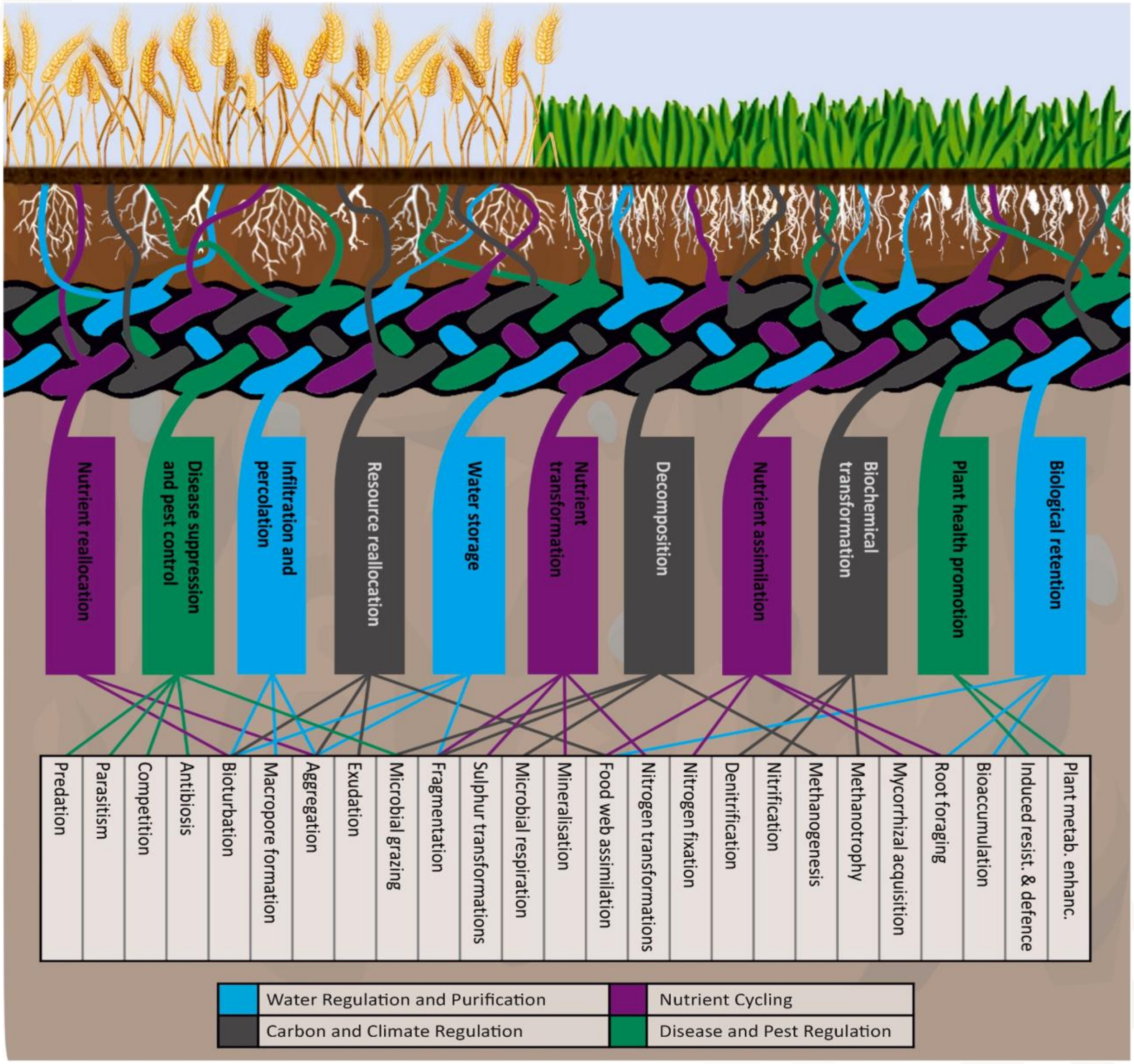


Figure 5.1. Conceptual overview of how soil quality is affected by multiple soil functions simultaneously: Water Regulation and Purification (blue), Nutrient Cycling (purple), Carbon and Climate Regulation (grey) and Disease and Pest Regulation (green). Soil life performs a plethora of processes (beige boxes) which support one or more soil functions. Bundles of related processes, or sub-functions, (coloured boxes) structure the contribution of soil life to each soil function extracted from Creamer et al. (2022).

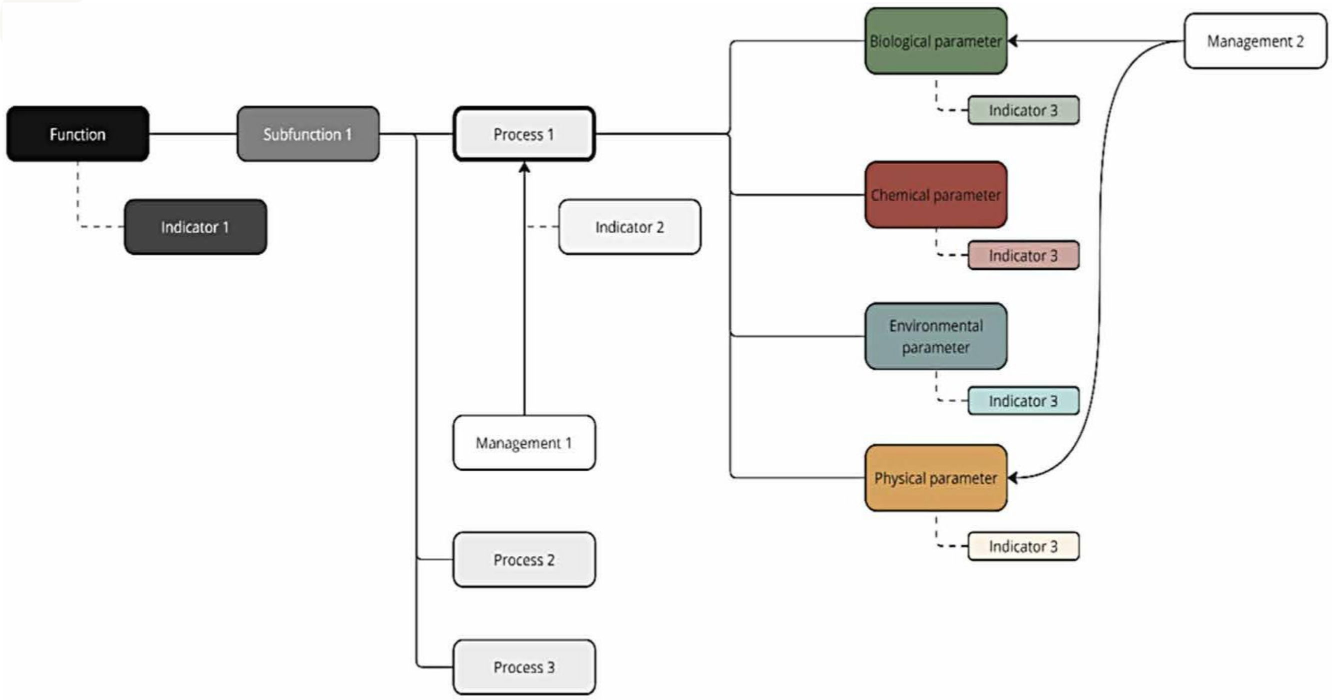


Figure 5.2. Soil function cognitive model describing the interaction between soil functions, sub-functions, processes, parameters and their associated indicators extracted from Vazquez et al., (2025). The indicators identified at each level of the diagram and the indicators used for monitoring purposes should be selected at higher levels of the hierarchy. The indicators at the function or process levels are not always available and indicators at lower levels of the diagram will be needed. In this case, the indicators representing all types of parameters should be selected.

5.3.2 *Sensitivity and specificity*

Soil biological parameters are sensitive to soil management, therefore, when selecting soil indicators, it is important to consider the sensitivity of the method to management and spatio-temporal variation (Zwetsloot et al., 2022). The key attributes of effective indicators are their potential to detect significant change over an appropriate time scale. It is important not to select indicators that demonstrate high variability due to spatio-temporal variations. Soil indicators must be sensitive enough to detect changes in soil conditions while remaining specific and resistant to excessive levels of noise. It is useful to select indicators that fluctuate significantly on a daily or weekly basis for long-term monitoring purposes (Robinson et al., 2024).

5.3.3 *Targeted indicator selection*

Selected indicators must be relevant to the scope and SDG. This defines the relevance of selected indicator to the specific context and question and being addressed (for example, its applicability across spatial and temporal scope of interest, area of concern) and context of SDG (Gebara et al., 2024; Bünemann et al., 2018). Gebara et al., (2024) ranked the level of importance of indicator selection on a scale of level A (mandatory for indicator selection to comply) to level B (recommended for indicators to comply to the furthest extent possible). Selection of indicators based on their relevance to the scope and to SDG was ranked in level A and can be assessed semi-quantitatively (categorical or binary scale). It is important to evaluate if the selected indicator is relevant to the spatial and temporal scope, area of concern, target audience and aspects of the SDG under consideration.

Robinson et al., (2024) emphasized the importance of careful selection of indicators particularly when assessing ecosystem service delivery and the significance of using a range of indicators targeted at specific questions and processes. They reported the outcome of a recent review commissioned to support the development of England's Environmental Land Management (ELM) scheme, monitored through the England Ecosystem Survey (EES) and evaluated over 740 land management interventions against 53 ecosystem service indicators. Observations from the review indicated few win-win solutions for land management across the range of indicators and the most effective interventions were identified as priorities for only three ecosystem service themes. Also, the choice of indicator within a given ecosystem service significantly influenced the outcome of the assessment underscoring the importance of using wide range of indicators designed to specific processes and policy questions.

5.3.4 *Validity and reliability*

Its mandatory for indicator selection to be scientifically robust and comparable across time, space and field. It is also recommended that the measurement of the indicator is carried out using high quality, reliable data that is easily accessible using limited resources (Gebara et al., 2024). Validity and reliability are important factors to consider when selecting indicators for the purpose of long-term monitoring (Robinson et al., 2024). Due to evolving technologies which may render some methods not useful for long-term monitoring, some measurements have limited lifespan. Although simple, tried-and-tested metrics may lack novelty, however, they may be useful in providing reliable data on the long-term. Parameters such as pH, SOM (loss on ignition), bulk density and electrical conductivity have shown to be reliable consistently over long periods of time in soil monitoring. On the contrary, it remains challenging in selecting biological indicators. This is because of the ongoing development of the metrics and rapid evolution of methods especially those related to DNA-based analyses. It is possible to select suitable methods to obtain the state of a specific metric, but their long-term suitability is uncertain (Robinson et al., 2024).

Furthermore, Robinson et al., (2024) reported that extensive field protocols and robust laboratory quality assurance procedures are needed to reduce variability and increase reliability. This is particularly important for large scale and long-term monitoring programs where staff turnover, surveyors and equipment are unavoidable. For example, in the CS and ERAMMP programs, a dedicated two-week training program is carried out yearly before each field season. This training program is comprehensive and covers both practical and theoretical aspects of the survey irrespective of the surveyors' initial experience. This guarantees consistency and data integrity across years and teams.

Due consideration must also be given to the method of processing the soil measurements. For example, if the soil measurements will be processed in the laboratory or through external laboratory. Processing of soil measurements in the laboratory is associated with additional costs but provides greater control measurement methodologies, though it may not always be possible. In external laboratory, it is important to ensure consistency of the methodology and preservation of the soil samples and transparent and accurate reporting (Robinson et al., 2024).

5.4 PROCESS OF INDICATOR SELECTION

Zwetsloot et al., (2022) developed a flexible biological method selection tool known as the Biological Soil Information System (**BIOSIS**) tool that supports the selection process of soil indicators across wide range of soil assessment programs targeting different stakeholders such as farmers, land management and policymakers. This tool (described in **Figure 5.3**) evaluates the process of the soil indicator selection method in relation to key soil functions relevant to temperate production systems: carbon and climate regulation, water regulation and purification, nutrient cycling and disease and pest regulation (Creamer et al., 2022). This tool structures the process of indicator selection into three different tiers: (i) pertinence to soil functions (ii) applicability to ecosystem under consideration and (iii) technical properties. The selection method is evaluated with respect to multiple selection criteria, assesses and assigns a numerical score. The final output of the BIOSIS tool is a ranked list of indicator selection methods and each method is accompanied by a score calculated through a combination of multiplication and addition algorithm. A selection method is excluded from the output if it receives a final score of zero and a higher score indicates that the method is more suitable within the specified context. However, these scores should not be followed blindly because multiple methods may be recommended for the same process or actor, and the tool may not fully account for the nuanced user preference (Zwetsloot et al., 2022)

Furthermore, Vazquez et al., (2025) provided more illustration on the process of indicator selection. They reported that this process was conducted through a structured and interactive process involving scientists and 25 soil experts engaged in diverse range of soil health across Europe, that gathered in both online and in-person workshops. In this work, they identified and ranked processes relevant to four key soil functions. This process laid the foundation for each of the soil function cognitive models that integrated the biological, chemical and physical soil expertise with landscape and modelling experts. The relevance of the processes and parameters were ranked based on their importance in specific soil function and ecosystem service delivery using a scale from 1 (very important) to 3 (less important or relevant) (Vazquez et al., 2025).

This method of indicator selection as proposed by Zwetsloot et al., (2022) progressively narrowed down a broad list of processes and parameters using defined selection to arrive at a final set of indicators, and it funded the approach described by Vazquez et al., (2025). This selection process operates through several key steps. The first step is (1) pertinence to the soil function, which first evaluate indicators based on their relevance to the specific soil function under consideration. This ensures that each selected indicator provides significant impact into the processes and sub-functions that underpin that function. The second key step is (2) applicability to context which allows indicators and associated methods to be assessed for their suitability within the specific context of the monitoring program taking due consideration such as land use type, spatial scale of assessment and prevailing environmental conditions (Vazquez et al., 2025). Third is the technical criteria that considers whether the indicators are further assesses based on technical considerations such as the ease of interpretation, throughput, measurement accuracy, cost and practically of implementing the associated measurement techniques (Zwetsloot et al., 2022).

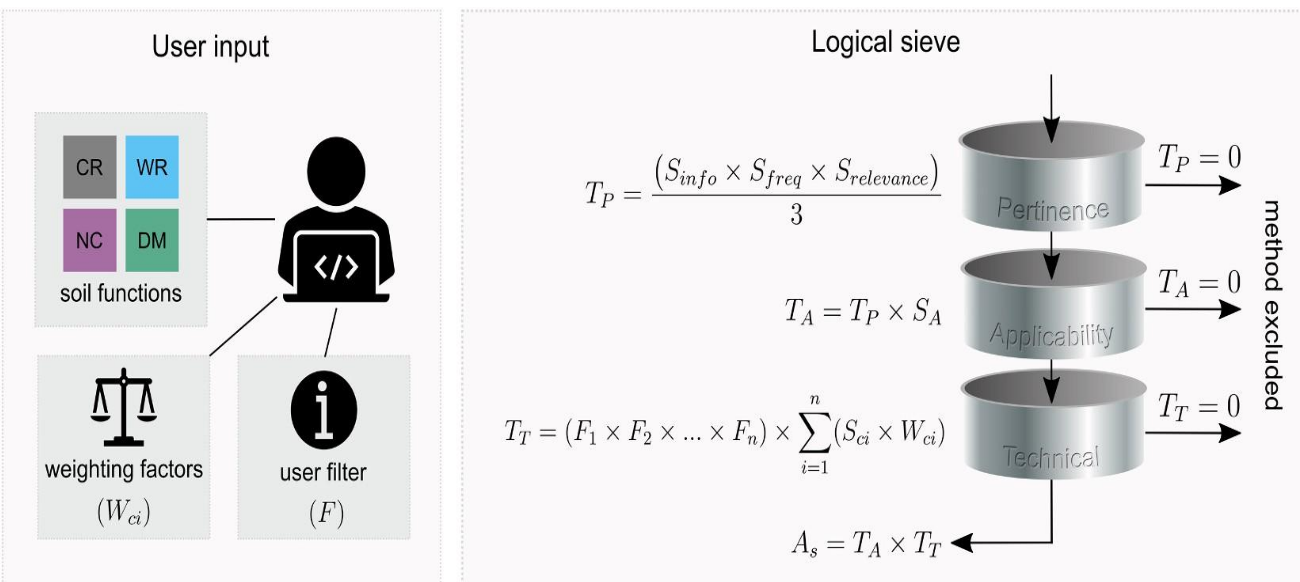


Figure 5.3 A flexible biological method selection tool (BIOSIS tool) adapted from the original logical sieve framework described by Zwetsloot et al., (2022)

CONCLUSION

This report has provided an up-to-date overview of the frameworks and considerations in the selection of indicators for soil health assessment and evaluation. Selection of SHIs is critical. SHIs are parameters or metrics derived from physical, chemical and biological properties which describe the condition of the environment, impact on human health, wider ecosystems and materials and their potential to deliver significant ecosystem functions and services. Therefore, it is imperative to assess and evaluate the capacity of soil in providing these relevant ecosystem services and functions through the four distinct frameworks identified and described in this report. The frameworks articulated in this report serve as standard benchmarks and value frameworks for quality assessment. In addition, because of the importance of soil in climate change regulation, nutrient cycling, sustainable food production and sustainable development goals, reliable approaches are critical in selecting adequate thresholds applicable in evaluating the capacity of soil to provide the required ecosystem functions and services. Soils play important roles in our communities and environment by contributing to food security and diversity; therefore, it is essential to monitor the state and change of soils in a robust, transparent and efficient manner. This will provide relevant information and feedback whether soils are providing the required services and if there is need to effect any change in the management method.

Soil monitoring is an important complementary activity to soil health assessment, especially when using a target/threshold framework. Evaluating soil indicator data against defined targets and thresholds supports the long-term sustainability of agricultural systems and the ecosystems they influence. At the EU level, a future approach may involve developing a harmonised model by integrating data from national datasets and European datasets, enabling coverage across diverse climates, soil types, and the full spectrum of selected indicators. The principles established in this report set a framework with clearly defined objectives, achieved through robust statistical sampling design. Indicators are selected based on criteria that support statistical rigour and are presented in indicator-specification tables aligned with policy-relevant soil functions. The key elements of this framework include the monitoring objectives that describes the purpose, adaptability, accessibility, transparency, ethical considerations, and timeliness, the sampling design that defines functional reporting units, design structure, and cost-effectiveness. Key criteria of indicator selection are based on sensitivity, specificity, measurability, targeted selection, and validity and reliability.

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Appendix 1: Continental Scale Soil Monitoring: A Proposed Multi-Scale Framing of Soil Quality

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Abstract: Globally, soils are subjected to various management practices and stressors which can lead to degradation. This makes their protection essential for sustaining many functions and services as well as maintaining the overall life support system of Earth. National monitoring programmes are increasingly implemented to evaluate the state and trend of soils, a move which has been advocated by Mission Soil in Europe. In soil science, frameworks have been established to interpret and communicate soil monitoring results, concentrating on the concept of quality, a term which can be interpreted in many ways. This paper explores the multifaceted meaning of soil quality, addressing its implications for future soil health assessments. It achieves this by focusing on the context of Mission Soil. Soil health is a holistic concept embracing emergence, complexity and highlighting long-term vitality and resilience. In contrast, soil quality is often viewed through the lens of its capacity to meet specific human needs and functions, typically in a shorter timeframe. The concept of quality is assessed through indicators where the choice of framework significantly influences selection and interpretation. However, selecting appropriate soil indicators across Europe is challenging due to diverse climate, topography, geology and soil types, resulting in varied soil processes. Therefore, establishing clear principles and criteria for

soil indicator selection is essential. Our paper identifies four distinct frameworks for soil quality assessment: 'Fitness for Purpose', 'Free from Degradation', External Benchmarking' and 'Value Assessment', with each possessing a unique role and application. Notably, the 'Free from Degradation' framework is emphasized for its alignment with soil protection efforts and its relevance to soil threats. This makes it particularly suitable for pan-European assessments conducted by the European Union Soil Observatory (EUSO).

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Appendix 2: Four approaches to setting soil health targets and thresholds in agricultural soils

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Abstract: Soil health is a key concept in worldwide efforts to reverse soil degradation, but to be used as a tool to improve soils, it must be definable at a policy level and quantifiable in some way. Soil indicators can be used to define soil health and quantify the degree to which soils fulfil

expected functions. Indicators are assessed using target and/ or threshold values, which define achievable levels of the indicators or functions. However, defining robust targets and thresholds is not a trivial task, as they should account for soil, climate, land-use, management, and history, among others. This paper introduces and discusses (through theory and stakeholder feedback) four approaches to setting targets and thresholds: fixed, reference, distribution and relative change. Three approaches (not including relative change) are then illustrated using a case study, located in Denmark, Italy, and France, which highlights key strengths and weaknesses of each approach. Finally, a framework is presented that facilitates both choosing the most appropriate target/threshold method for a given context and using targets/ thresholds to trigger follow-up actions to promote soil health.

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Appendix 3: Five decades' experience of long-term soil monitoring, and key design principles, to assist the EU soil health mission

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Abstract: The European Union has a long-term objective to achieve healthy soil by 2050. The European Commission has proposed a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law, SML), the first stage of which is to focus on setting up a soil monitoring framework and assessing soils throughout the EU. Situated in NW Europe, the UK has substantial experience in soil monitoring over the last half century which may

usefully contribute to this wider EU effort. A set of overarching principles have and continue to guide design of national soil monitoring and may prove helpful as other European countries embark on similar monitoring programmes. Therefore, we present the principles of design from five decades of national soil monitoring. The monitoring discussed is based on a stratified-random design, has matured in support of policy questions, and operates over space and time scales relevant to SML. The UK Centre for Ecology & Hydrology (UKCEH) Countryside Surveys (CS) of Great Britain and Northern Ireland, Welsh Government, Environment and Rural Affairs Monitoring and Modelling Programme (ERAMMP) and the England Ecosystem Survey (EES) monitoring programme are national programmes currently operating in the UK. Some important lessons learnt include adopting a question-based approach; having a clear robust statistical design for the purpose; selecting indicators that address policy and underlying scientific questions; and selecting indicators that can detect change and use robust and well-tested methodologies across a wide range of soil and land use types, remaining valid over long time scales, supporting thinking long-term. Technical lessons learned include the proven cost effectiveness of a stratified-random design including replication, while adopting a common stratification layer of stable environmental attributes aids comparability between monitoring programmes. Common protocols are vital for future intercomparisons, but a full ecosystem approach that includes co-located soil and vegetation samples for interpreting a co-evolving system has proved hugely advantageous. UK monitoring programmes offer a range of experience that may prove valuable to future soil monitoring design to address the major societal challenges of our time, such as maintaining food production and addressing climate change and biodiversity loss

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