AI4SoilHealth

Indicator selection framework with protocol for AI4SoilHealth

D3.1

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HISTORY OF CHANGES		
Version	**Publication date**	**Changes**
1.0	19/3/2024	• Initial version
1.1	16/4/2024	• Updated after internal and external review

Contents

1. Introduction

The aim of deliverable D3.1 within the AI4SoilHealth project, was to review, examine and create a robust selection framework for assessing appropriate Soil Health Indicators (SHIs) as part of a probabilistic based monitoring framework. This was based on policy and stakeholder needs from WP2 – including consultation with the Joint Research Centre's (JRC) Land Use and Coverage Area Frame Survey (LUCAS) soils team – and synthesizing previous soil health indicators based on literature, policy and known databases across the EU, UK and elsewhere.

This report provides a robust framework for assessing and selecting appropriate SHIs. This framework is constructed upon a set of agreed selection criteria. The selection of the SHIs will ultimately depend on their ability to detect state and change (mean and variance) relative to the desired soil ecosystem functions and services the soils can provide.

This deliverable will be crucial in working towards meeting the eight European Union (EU) Mission Board targets set in the Soil Mission Implementation Plan. Furthermore, the Mission Board identified eight SHI channels within which the proposed framework, reported in this deliverable, can be used as a basis for testing and further enhancing these SHIs. The selection criteria will also serve for choosing future indicators and will be aligned with the Soil Monitoring and Resilience Directive proposal. It is further expected that D3.1 will help formulate future work across other WPs within the AI4SoilHealth project. This will notably be important for D3.2., which will build on D3.1, by investigating new indicators to address issues raised generally or from deliverable outcomes from WP2. D3.2 will use the framework produced in this report as a template for indicator assessment.

This deliverable will provide recommendations across other WPs within the AI4SoilHealth project, notably in connection to future assessment, measurement, and monitoring of soil health across the EU.

2. Defining Soil Health and its origins

The term "*soil health*" is used widely by various stakeholders such as land managers, farmers, governments, scientists, and academics and can mean different things depending on the target audience and context. Therefore, it is critical to distinguish what soil health refers to from the outset. For the purposes of D3.1, **soil health** is defined according to the EU Mission as:

"*The continued capacity of soils to support ecosystem services, in line with the Sustainable Development Goals and the Green Deal*" (Mission, 2021).

Soil health is said to have been first utilized during the 1910s (Brevik, 2018; Harris et al., 2023) but has been widely applied in the soil science community since the 1990s (Harris et al., 2023; Powlson, 2020). A desire for healthy soils has provided the basis for recent policy targets proposed by the Mission Board for Soil Health and Food where they state that "*healthy soils must provide ecological functions for all forms of life, in line with the Sustainable Development Goals (SDGs) and the Green Deal*" (EEA, 2023). Crucially though, soil health must be relevant and understandable to a range of stakeholders (e.g. agriculture, policy, supply-chain management, finance and business and academic research) for these targets to be achieved (Lehmann et al., 2020).

The proposal of a Soil Monitoring and Resilience Directive (Soil Monitoring Law SML) (EC, 2023) adopts the following definition: "*soil health means the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services*". The European Parliament Committee on the Environment, Public Health and Food Safety (ENVI) Report (EP, 2024) proposed the following amendment "'*soil health' means the physical, chemical, **functional** and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services, **taking land use into account."***

3. Soil threats and functions

Soil health assessment can be heavily influenced by threats such as degradation, loss of organic matter, pollution, compaction and erosion (Lehmann et al., 2020; EEA, 2023). These threats, occur worldwide and impact food production across Europe. For the context of this report, **soil threats** are indicative circumstances which can damage or reduce a soil's capacity to provide ecosystem services (Baritz et al., 2021). Soil threats will negatively affect a soil's characteristics (physical, chemical, and biological) preventing them from performing to their optimal functionality (EEA, 2023). Counteracting soil threats has been a continuous challenge for all EU Member States for decades and has been discussed in depth following the introduction of the EU Soil Thematic Strategy (EC, 2006).

Any assessment of soil threats (e.g. soil erosion, soil degradation) must address to what extent a soil's functioning is affected (EEA, 2023). Soils are well known for providing a varied range of functions that contribute to goods and services which society depend upon (Haygarth and Ritz, 2009; Vogel et al., 2020; EEA, 2023; Ritz et al., 2009). These can range from producing food and fibre from agriculture, the capacity to store water, the ability to improve air quality and the capability to filter soil pollutants (EEA, 2023). Soils are also important stores for soil organic carbon, can provide nutrients for plants and provide habitats for soil living organisms.

As part of the AI4SoilHealth project, it is important to have a platform that informs stakeholders on a range of soil information, documents, or datasets. This can be in the form of soil properties, threats, functions or ultimately, soil health and associated indices. It will also be important for this This platform address what knowledge is already available and discuss what future research needs to be conducted.

4. Current datasets and future assessments of soil health

The ESDAC (European Soil Data Centre) is an example of an online platform service which hosts a range of pan-European and global datasets, soil-related documents, and maps (Panagos et al., 2022). Within ESDAC, there are over 30 datasets which address soil threats and related information. An example of this is the recently designed European Union Soil Observatory (EUSO) Soil Health Dashboard (EUSO, 2024 - https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/).

The EUSO Soil Health Dashboard is an assessment tool that is conveyed through key measures which are updated regularly when new data becomes available. This platform makes soil data more accessible to users through an interactive service and can provide a useful visualisation tool to chart the progress of reducing pressures on soil over time. An assessment tool such as this can help to provide evidence about how much soil degradation is taking place across the EU and can help to support the policy case for the SML. The assessment tool will also help guide the '*EU Mission: A Soil*

Deal for Europe', where soil health monitoring will be discussed. The Soil Strategy 2030 lists several actions for EUSO development, among which (i) identify, with the contribution of the European joint programme, on agricultural soil management, soil monitoring gaps, in dialogue with Member States and other key stakeholders, (ii) Develop a soil dashboard with a set of reliable soil indicators integrating trends and foresight, and (iii) Develop an EU inventory of soil biota in order to monitor and better understand soil biodiversity.

The Land Use and Coverage Area Frame Survey (LUCAS) is another example of a dataset that can be utilised to better understand soils across Europe. LUCAS is an extensive and regularly conducted survey of soils that is carried out across the EU. The main objective of LUCAS is to gather data by sampling and analysing soils and assessing the effects of land management activities to provide useful information for policy and decision makers (Orgiazzi et al., 2017). The LUCAS dataset has been widely recognised as one of the most comprehensive, harmonized soil monitoring databases worldwide due to the range of properties analysed and its ability to provide freely available data from the open access ESDAC service (Orgiazzi et al., 2017; Panagos et al., 2012). There is an acknowledgement across EU Member States that there is a need to develop guidance on how certain soil health indicators can be measured and assessed. This has been magnified since the recent proposed SML.

5. Taking a question led approach

Identifying and addressing societal challenges as well as policy questions can provide appropriate context for monitoring soil health. Key questions encompass a range of areas (e.g. management of productivity and farming, including the food chain and human and animal health; climate change including mitigation and weather extremes such as flood, heat and drought; pollution including contaminants, water and air quality, and ecosystem health and biodiversity). With regards to challenges such as Net Zero (i.e. carbon offsets from land to balance residual emissions), the question of what works where is fundamental to finding solutions. Such an initiative of Net Zero connecting to soil consumption was recently developed in Switzerland and passed by the government as they move towards NetZero by 2050. Monitoring natural resources such as soils enables informed choices to be made and was recommended in the United Nations' (UN) Intergovernmental Technical Panel's World Soil Resources Report (FAO and ITPS., 2015). The Sustainable Development Goals (SDGs) have also intrinsically mentioned soils in some way, and these have been documented in a recent EEA (2023) report.

Soils are continuously considered and connected with other natural resources and as a result, goals set by policies have been put in place to mitigate climate change, protect nature, eliminate pollution, and ensure sustainability of the food system. This can be achieved by preventing soil contamination as well as finding ways to sustainably use soil more effectively. This can be achieved by moving from a threat-based approach to a functioning philosophy by investigating soil state and changes to soil conditions. Furthermore, activities that have multiple benefits such as soil health, biodiversity, and climate should be addressed.

Usually, soil friendly measures can provide opportunities to promote good practices and diversity by scaling up local initiatives. This can be achieved through a range of EU policies and goals, procedures, and limits such as the Nature Restoration Law. An example, the "Impact of the CAP on sustainable management of the soil" (EC, 2021) evaluation study highlights how the lack of a common definition of soil health is. Furthermore, the limited availability of data complicates the assessment of how EU soil-related practices – fostered by CAP instruments – have (or have not) contributed to soil/soil components quality. The evolvement of the SML has been set up in large part due to unambitious targeting and limiting standards (ECA, 2023). Setting up EU soil strategies and monitoring frameworks (e.g., SML) should ensure coherence across EU initiatives and promote the integration of soil considerations in the design, enforcement, and evaluation of EU policies.

One of the overarching frameworks used by policy makers within the EU is to assess such activities commonly used in the Drivers, Pressures, State, Impact, Response framework (DPSIR) and this is described in the following section.

6. Policy and asset management: The role of the DPSIR framework

The DPSIR framework was designed to describe interactions between society and the environment (Gabrielson and Bosch, 2003). It is a support mechanism that has been adopted by the European Environment Agency (EEA) to assess the pressures and risk of failing to meet certain environmental quality objectives (Hall and Voulvoulis, 2008). The DPSIR framework has been used for various activities such as assessing pressures from agricultural land use to the impacts on surface and groundwater (Giupponi and Vladimirova, 2006). It has since been extended to better illustrate the connections between driving forces, pressures, states, impacts and responses (extension of the PSI model developed by OECD, 1993) (EEA, 2023). A graphical representation of DPSIR is shown in **Figure 1.**

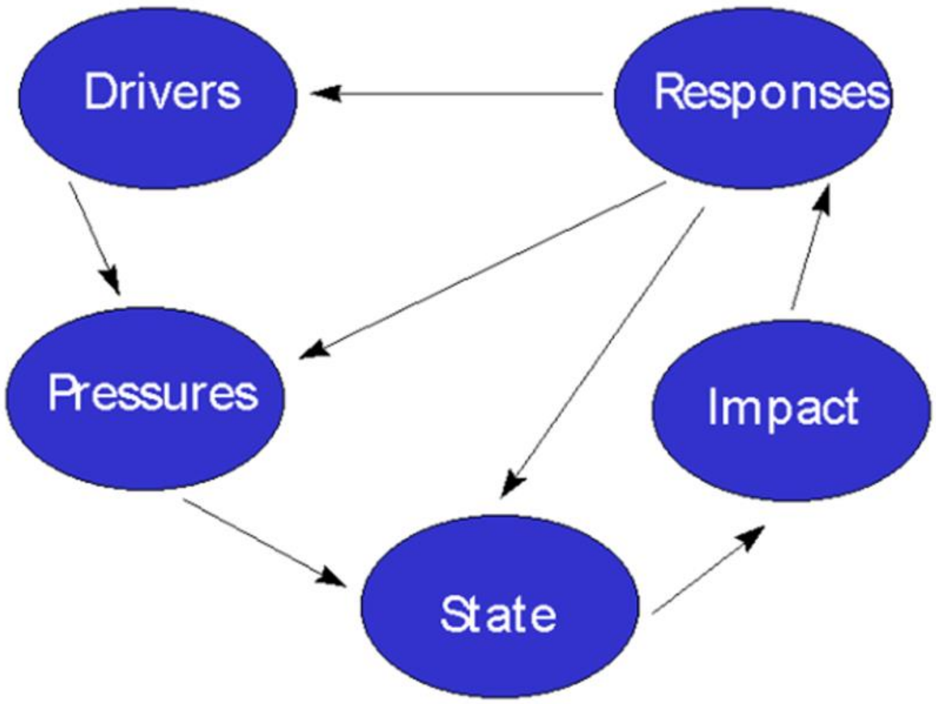


Figure 1: DPSIR conceptual framework from EEA, (2023).

7. Indicators

The DPSIR framework is evaluated from investigating a range of soil health indicators which can provide the backbone to subsequent research and analyses. Indicators applied in the DPSIR framework can be outlined across three different groups. The first of these considers measures linked to environmental pressures (**P**) which can relate to human activities being exerted on the environment. These can be proximate pressures, which can have direct consequences or impacts on the environment or can indirectly lead to proximate pressures at a later stage. The second of these groups concerns measures connected to environmental conditions corresponding to a state (**S**). These measurements are often reflective of policy or environmental management objectives. The final category relates to indicators which are connected towards society's response to environmental changes (**R**). These can be individual or collective actions to help adapt, mitigate, or prevent negative impacts on the environment which are human induced. These can also be used to halt or reverse already inflicted environmental damage. As the environmental policy arena continually evolves, new indicators are often required to help address new or emerging issues. Concurrently, technology changes and develops. Hence, it is important to know the developmental state of indicators. What must be acknowledged is that a good soil health indicator or indicator value found in one soil type, habitat or environment can be less relevant, classified as unhealthy or unrepresentative in another. Thus, a soil health matrix or soil data cube approach will be required to take this into account and aggregate out uncertainties. This is something that will be a critical output from the conclusion of the AI4SoilHealth project.

Soil health can be classified using a collection of physical, chemical, and biological indicators (Jian et al., 2020). An **indicator** in this regard, can be defined as:

"a *parameter or value derived from measurements that provide information about a phenomenon, or a specific aspect of soil health*" (OECD, 1993, Faber et al., 2022).

Indicators can be measured through a range of approaches including analytical or laboratory methods, statistical modelling, or expert knowledge-based systems, gathered quantitatively, qualitatively, or by a combination of both. Soil health indicators can possess two major functions: to reduce the required number of measurements in order to assess the response of an asset, environment, phenomena, or a system and to communicate a response to a stakeholder. It is important to note that Indicator A (e.g. Soil Organic Carbon) and Indicator B (e.g. bulk density) might both be very informative if collected alone, but if both are collected simultaneously there maybe overlap in terms of correlation and redundancy, this may mean that little effort is saved; however, it may lead to greater confidence in a synthesis or analysis as indicators can be cross checked.

The selection of appropriate soil health indicators is therefore dependent on a range of societal goals, socioeconomic and environmental objectives and as result, different weightings may be most appropriate to use depending on parameters (Bone et al., 2014; Arshad and Martin, 2002). This has been addressed in the past using a tiered approach. However, there is no consensus in the soil science literature as to what should distinguish these tiers. This next section will examine how best to address this.

8. A tiered system for soil health indicators

The Inter-Agency and Expert group on Sustainable Development Goals (IAEG-SDGs) provided definitions for what a tiered system for soil health indicators should consist of (SDG Reporting, 2019). In their (2019) report, they suggest that indicators, which are conceptually understood, should be placed in the highest tier (usually Tier I).

Soil health indicators which are typically Tier I should cover a core set of metrics which broadly capture the response of soil health towards functions and other services which have been mentioned previously in this report. Tier I indicators should also have internationally established methodology with a sensitivity to state and change that makes them widely interpretable. Tier II indicators should be seen as measures that build upon the representative soil health covered by Tier I with future indicators or those that need further development either sit in a Tier III or be classified under future metrics (**Table 1**); or metrics for educating or providing context at a local scale, such as the previously mentioned pH using an indicator solution. The IAEG-SDGs do, however, acknowledge that some indicators are being regularly developed and tested.

As an example, an indicator is not just a measured soil property, but rather a "*soil property measured in a specific way with an uncertainty*". For example, soil pH estimated in-situ by an indicator solution (Hellige) has a large measurement error, thus the sensitivity is too low to serve as a national or pan-EU indicator, but it might be useful at the farm level providing some context for the current soil state. It wouldn't make it as Tier I indicator (discussed below), even if it would be widely available and thus would always be Tier III. Soil pH determined by VisNIR spectroscopy on a dried sample could qualify as a Tier I indicator, if the prediction error of the spectral function is within an acceptable range (but only then). Thus, the favoured Tier I soil pH indicator would be a laboratory method using an electrode, measured using a standard approach in a prespecified solution and dilution (Tier I, widely available and accepted). It is important to remember there are a number of standard approaches that are acceptable, and hence there is a need to select one of these.

Table 1: Tiered System for Soil Health Indicators

Tier	**Criteria**	**Example Indicators**
I	Commonly accepted indicators that provide fundamental insights into soil health; have internationally established methodology.	pH, Soil Organic Carbon, bulk density
II	Data not regularly collected or relevant for specific geographic regions.	Electrical conductivity, soil temperature
III	Less commonly used, specialised and require increased testing and development.	Soil fauna, enzyme activity

The adoption of a tiered approach for EU Soil Monitoring is currently under discussion at the European Parliament due to the SML amendment proposed by the ENVI Committee.

There have been several ways of selecting soil health indicators in previous academic literature (for more information (see **Appendix 1)** and the next section aims to address some of these approaches.

9. Introducing a development framework for effective indicator selection

Debates continue about the most useful indicators for understanding soil health across different scales. To reduce complexity, it is essential to gather the most relevant measures, especially those connected to land management practices (Bünemann et al., 2018). Increasingly, the cost of gathering certain measurements (e.g., DNA sequencing and enzyme activity) can become unmanageable, particularly if detailed soil biological parameters are included. Furthermore, there are multiple challenges with costs, scale and relevant policy questions which need to be addressed in the context of soil as well as assessing what issues require the greatest prioritization. No single measurement can address all of these, so multiple measurements are required. From this set of robust indicators, selections can be made to address specific societal challenges or policy questions.

Different approaches have been taken to select a minimum dataset of soil health indicators in an effective and suitable manner. Existing minimum soil health indicator datasets have been based upon expert knowledge (Doran and Parkin, 1996), multivariate techniques (Lima et al., 2013; Shukla et al., 2006) and regression approaches (Kosmas et al., 2014). From evaluation of these methods, the typical number of indicators selected usually ranges between six and eight (Bünemann et al., 2018). However, it is important that validation of the minimum dataset is conducted since although some soil properties selected may be good for soil functioning, they might not present much variation within the study area (Bünemann et al., 2018).

Ritz et al (2009) presented a participatory approach as an alternative method to selecting the appropriate minimum number of soil health indicators. Their approach allowed stakeholders to score measures using a "*logical sieve*" which was consequently weighted after multiple iterations. This method has since been modified by other authors for establishing appropriate proxies of soil health (Stone et al., 2016). Other approaches such as Bayesian Belief Networks (BBNs), highlighted in work by Troldborg et al. (2013), have also been discussed with their method being seen as positive in assessing soil health because it reduces complexity, reduces expense, and is not laborious.

Adding new soil health indicators into minimum datasets has been frequently discussed, particularly if these are seen to add value from the perspective of management goals and can be universally applied across habitats and environments. Future soil health assessment schemes and strategies will benefit from recent improvements in soil biology, spectroscopy, and soil science (Bünemann et al., 2018). However, the determination of change in the soil property remains a challenge for many emerging techniques. Moreover, these indicators are most practical if a set of values can be interpreted in the context of reference values to show where this sits in a particular environment against the wider world. Such reference values can be provided from literature or by expert knowledge to appreciate the performance of the measurement within a particular environment (Doran and Parkin, 1994). However, such values are not always available, nor dependable, and alternative strategies must be examined. This has been partly addressed in recent research by Feeney et al., (2023) who tried to establish a range of benchmarks for multiple soil health indicators (soil organic matter, bulk density, pH, and earthworm counts). They did this by assessing their relationships with a range of soil and land use types across Great Britain.

Given how the DPSIR framework operates, several factors need to be considered to make sure the indicators selected are fit for purpose in addressing soil threats and shaping future policies. The OECD (1993) and Lehmann (2021) initially used three factors: relevance to policy, analytical soundness, and measurability to select appropriate measures. This has since been enhanced by UKSIC (Merrington, 2006) and Bone et al (2014), where other criteria have been discussed.

This report develops upon this strategy and aims to create a robust indicator selection process which is discussed in the section below.

10. Criteria for robust indicator selection

Robust indicators must be able to not only measure the state of the system but also how it changes. This usually relies on measuring the mean and variance of the indicator. To differentiate this, probabilistic indicators (pH, SOM, bulk density) form part of a statistical monitoring framework whereas stakeholder comparison indicators (Visual assessment, earth worm counts, tea bag test, cloth degradation tests) are used to convey to stakeholders' differences in soil properties on the ground. There is overlap between the two, but the emphasis here is on those probabilistic indicators that are used in regional to pan-EU monitoring programs. For these, the following criteria should be considered:

10.1. Relevance

A soil indicator must be relevant, not just in a particular environment but also how it responds to change. The indicator being considered must be easy to interpret (usually quantitatively) and be effective in identifying temporal change(s). It might be useful to select indicators which are either directly or indirectly connected to soil functions, threats, or ecosystem services (Bünemann et al., 2018). Bone et al., (2014) believe a relevant indicator is one that can be collected across a range of soil types (e.g., pH, soil organic matter, bulk density).

10.2. Sensitivity, discrimination, and signal-to-noise ratio

The second criterion in the framework focusses on sensitivity, discrimination, and signal-to-noise ratio. Due to the spatial variability of soil indicators, it is not unusual to have large standard errors for many whilst others will change only slowly over time. Therefore, selecting appropriate indicators, which encompass long-term monitoring, must be considered to distinguish long-term relationships as well as abnormal events.

To select the most appropriate soil health indicators, it is crucial to consider the probability of detecting significant changes against the sampling measurement intervals. Different sampling intervals will determine how an indicator behaves across an environment.

It is critical to take into consideration *undetected change.* Indicators should be selected and examined over time where significant changes will go *undetected*; and whether such changes, once detected, are already irreversible. These aspects can be determined using statistical analyses. It is also important not to select measures that are likely to produce high spatial or temporal variability or be subject to sampling and measurement errors. Bone et al., (2014) states that selection of appropriate SHIs should be robust and interpretable for the soil system.

Sensitivity to management changes also needs to be considered, although seasonal variation can play a large part in selecting appropriate indicators (Bünemann et al., 2018). It has become commonplace for some indicators (e.g., carbon, pH) to be monitored over time across sampling campaigns. However, for some indicators, particularly biological ones such as soil biodiversity, this can be difficult to gather because further investigation work is required to identify species and subsequent activity (e.g., respiration) taking place in the soil (Morvan et al., 2008).

10.3. Measurability and Practicality

The third aspect to consider is how practical an indicator is for the environment being investigated. It is important to investigate how theoretically understood and respected the specific measured soil health indicators are measured in their current form and if these are not robust, examine how well developed they are. Such unique indicators may need to be selected because there is no other appropriate way to gather the information or that the method is inexpensive and straightforward to use (Bone et al., 2014; Bünemann et al., 2018). It will also be important to reflect upon indicators which have been collected in disturbed areas (e.g., due to management activities) as this can provide skewed results (Idowu et al., 2008).

A further aspect of measurability is future proofing measurements when selections are made. pH, bulk density, and Loss-On-Ignition (LOI) for determining Soil Organic Matter (SOM) are simple and robust measures that have stood the test of time. Thought should be given to whether a measurement technique will still be comparable with upgrades over the next 40+ years. Some measurements offer exciting potential but changes on 5–10-year time cycles or less render them unsuitable to detect change over time.

In addition, soil science is constantly looking for new ways to probe soil, and this often results in multiple ways of measuring the same metric. Therefore, agreeing on a set of protocols is beneficial critical as well as the development of transfer functions from one method to the other if required. The measurement of pH would seem trivial; however, it can be measured in different dilutions at different soil to water ratios, and determined on field moist or air-dry soil, all of which add subtle differences. As a result of this, it can make comparisons, especially for change, challenging.

The same can be said for the use of remote sensing, which is appropriate for providing assessments of state, but can be challenging for measuring change. It's value can be demonstrated by the Copernicus Corine program which generates specific land cover change map products (Copernicus, 2024 - https://land.copernicus.eu/en/products/corine-land-cover).

10.4. Efficiency and cost

The fourth aspect should consider how efficient and cost-effective gathering SHIs are. There should be a vision to maximize the use of automated methods such as sensors and remote sensing and appropriate indicators should be evaluated against the need to minimize costs. Therefore, it might be more advantageous to select indicators which are only required to be gathered over a certain period (Bone et al., 2014) (e.g., once every 5, 10, 20 years). It is also important to consider whether the data is readily available and/or is easy to obtain at a reasonable cost. However, unlike some other natural resources, soil cannot be remotely sensed to depth. As a result, it is important to physically sample soil in monitoring campaigns.

When compared to other forms of monitoring and data collection, soil monitoring is relatively inexpensive. In the UK, the cost of the decadal 2011 national census was around GB£482 million pounds (€563.9 million euros), whereas Black et al (2008) estimated the cost of a decadal UK national soil monitoring program collecting and analyzing 4000 samples at GB£2.6million pounds (€3.04m euros). This is small in comparison to what was spent annually on water (GB£60.5 million pounds /€70.8 million euros) and air (GB£7.7 million pounds /€9.0million euros) in 2017-2018 in England alone (SSA, 2024 - https://tabledebates.org/research-library/england-spending-little-monitoring-soil-quality).

10.5. Surrogate indicators

Indicators that can be integrated or used as surrogates for other measures are useful. However, it is crucial to note that using these types of indicators should only be selected if they can provide increased knowledge and understanding across one or more key soil functions. Bone et al. (2014) also believes this is important, particularly from the viewpoint of pedotransfer functions, stating that SHIs collected should be used alongside with other measures to assess a soil's characteristics. For instance, spectral libraries for basic parameters have become useful in combination with pedotransfer functions and/or Artificial Intelligence /Machine Learning for functional soil health indicators and relations.

Whilst clay and silt contents (soil fines) are central, as they are fundamental properties, these can be complicated and costly to measure directly. However, these properties can be hugely important indicators for most soil health evaluations. Specifically, there are large spectral libraries located across EU, and a vis-NIR single beep on an air-dried sample can accurately predict soil texture (clay, silt, fine sand, and coarse sand), and helps to quantify SOM (SOC).

Adding texture to the classical parameters (e.g., bulk density and SOM) as combined input to pedotransfer functions or AI/Machine Learning can provide solid estimates of soil-water retention curve, both in terms of the dry-part relating to soil surfaces and wet-part connecting to the soil pore-size distribution.

ESDAC 2.0, alongside the LUCAS database, has embedded functions about mapping soil-water retention. Thus, spectral-based inputs, combining soil texture with pedotransfer functions or AI/ Machine Learning to predict water retention curves can be implemented. A similar example for soil chemistry would be CEC prediction from vis-NIR and spectral libraries in combination with pedotransfer functions based on clay, silt, SOM, and pH; or AI/ML approaches.

The best use of spectral libraries and determined metrics needs investigating. They represent a powerful tool. As previously mentioned, the issue surrounding the use of spectral libraries is their indirect measurement, sensitivity and measurement error. This becomes less of an issue for metrics used to contextualize indicators such as soil texture. However, it becomes an issue for state and change detection if the sensitivity and measurement error is less than a direct measure and less reproducible for a statistical interpretation. A key consideration is how accurate and precise does an indicator need to be for the purpose required and this is likely to change for different indicators.

Where measurement of a specific soil indicator is considered too expensive, difficult, or impossible to gather, pedotransfer functions can help to provide a proximate value using other indicators such as carbon and texture. This can be done for bulk density (due to the stoniness of the soil) (Bünemann et al., 2018; Reidy et al., 2016) and for hydrological features (Saxton and Rawls, 2006; Toth et al., 2015). However, pedotransfer functions are often suboptimal and this must be clearly stated, prior to, and after their usage (Bünemann et al., 2018). For instance, for the example of bulk density, only a mean bulk density can be estimated from clay and SOC. In other words, activities such as compaction by heavy machinery do not alter clay content but likely changes SOC due to a reduction in aeration. Thus, misinterpretation could be made as most pedotransfer functions would usually predict lower density, but it gets denser. Therefore, pedotransfer functions are rather useful more so to estimate potential or mean expected value (depending on how they were calibrated) rather than actual indicator values and changes.

10.6. Other considerations

There are other considerations when selecting appropriate soil health indicators. The first is scale. Different soil health indicators will be important for different areas depending on how large an area is along with its associated resolution. Scale can also be important on the political stage as different data from EU, national and regional authorities will be required depending on the corresponding responsibilities on the research, design, implementation and evaluation of policies within an area.

These spatial resolutions will be critical and valuable in terms of providing useful information depending on specific policies being considered and the economic impact that this might have.

Secondly, the availability of data and the time since collection of the data are important considerations for stakeholders, particularly policy makers; consistency in data collection is vital for the development of a time series. This is because sparse availability will not allow them to base legislation on soil indicators. Mapping historical and potential future trends with respect to soil health is useful. Some indicators (e.g. microbial activity) may be difficult to obtain, whilst others (e.g. SOC and pH) will be more tractable. Gathering soil indicator information at depth may also prove challenging, depending on the environment, the number of people involved in gathering the data and sampling strategies implemented. Different land cover types and land uses will influence the importance of selecting appropriate soil health indicators. As mentioned, many state indicators have uncertainties that are so high that they are of no use for detecting change.

There is an acknowledgement that some soil health parameters, which have been gathered previously, are still relevant. This is despite this data being collected over 30 years ago. The question that needs to be asked is how relevant they are in a changing world. Finally, the needs of stakeholders will be crucial in helping to identify which indicators might be of use in addressing key questions and problems. This will be important in addressing key policy questions.

11. Indicator selection table

Formalizing the selection criteria helps to consolidate the selection indicator framework. Such an approach was undertaken by Black et al (2008) and from this report, a modified version that can be used as a workplan for developing the Mission indicators (European Commission, 2023b). The Mission proposed eight indicators which can be viewed as channels within which robust indicators sit. The eight indicators are shown in **Table 2** below. Proposed links between mission objectives and the indicator channels can be found in **Table 3**.

Table 2: 8 Mission indicator channels

Indicator channel from EU Mission report
1) Presence of pollutants, excess nutrients, and salts
2) Soil Carbon
3) Soil structure including soil bulk density and absence of soil sealing and erosion.
4) Soil biodiversity
5) Soil nutrients and acidity (pH)
6) Vegetation cover
7) Landscape heterogeneity
8) Forest cover

AI4SoilHealth is planning to utilize the mission objectives and indicator channels as far as possible and examples of how this might be done can be found in **Table 3**.

Table 3: Potential relationships between Mission Objectives and Indicator Channels with the yellow highlighting main work areas in the AI4SoilHealth project.

	Indicator channels							
Mission objective	Presence of pollutants	Soil carbon	Soil structure	Soil biodiversity	Soil nutrients and pH	Vegetation cover	Landscape heterogeneity	Forest cover
Reduce land degradation	Y	Y	Y	Y	Y	Y	Y	Y
Conserve and increase SOC		Y				Y		
Reduce net sealing			Y			Y		
Reduce pollution	Y							
Prevent erosion			Y			Y	Y	
Enhance structure and habitat			Y			Y	Y	
Reduce global footprint								
Increase soil literacy	Y	Y	Y	Y	Y	Y	Y	Y

The purpose of the indicators is to inform policy and societal challenges with information regarding performance in terms of **major functions;** stating the linkage between an indicator and function is a key step for this to work effectively, and the **policy objective** is an important starting point.

Moreover, it is helpful to identify the **source** and level of the policy objective whether that be at national, EU, UN, or other scales.

Indicator Assessments should indicate the purpose of the indicator and outline what information it is intended to capture. The **Domain of interest** provides the scale over which the indicator is required to function effectively (e.g., Farm scale, NUTS1, NUTS0, Pan-EU).

Measurements made using an indicator can be expressed in terms of the type of **measurement**(s) and the **units** in which the indicator(s) can be determined. Moreover, in terms of addressing change, the **indicator assessment parameter** (e.g., mean, median, Standard Deviation (SD)) should be specified. The **indicator quantity** specifies the metrics to be measured. The **reporting unit** specifies the unit(s) for which an indicator is to be assessed. Management and reporting are generally conducted on a habitat basis, but it is also feasible to report on this using soil type as a foundation. The **type of result** should indicate in words what the expected result should address. The **tolerance level** sets a critical limit or baseline value if available and/or accepted. However, these may not always exist so other approaches such as benchmarking should be considered here. The **Action level required** can differ between the baseline value or critical limit, such that interventions are undertaken prior to those thresholds being reached. **Assessment interval** should be determined and be dependent on policy requirements as well as the sensitivity of the indicator and expected change. If indicators are being used to inform policy such that it can intervene, then ideally reporting should be within policy cycle periods to enable measurement development. The **soil sampling dimensions** should state the sample dimensions and sampling depth. **Appropriate sampling procedure** describes the standard methodology used for obtaining the sample while the **analytical method(s)** describes the precise measurement technique used to analyze the sample. Once samples have been collected, only a part of the sample may be used for analysis, some may be kept and archived. **Archiving** should be described, e.g., samples to be retained for microbiology analysis should be frozen. Archiving samples means that these can be retested should new indicators be developed or considered and there is a need to evaluate them over the monitoring period. Any **additional information** should be recorded.

An example of a table filled out for a robust soil carbon indicator is presented in **Table 3** and draft examples for other indicator channels can be found in **Appendix 2**. Such tables can be used to present a finished indicator or as a workplan for the development and testing of new indicators, such that new indicators should be able to address all criteria.

Table 3: Example of an indicator channel table filled in for a metric or suite of metrics. Several tables may be required depending on whether a channel has one or more indicators in the suite.

Indicator Channel: 2) Soil Carbon (Total Soil Carbon Concentration in Topsoil)	
Major Functions	• Food production • Climate mitigation • Hydrological regulation • Supporting habitats and biodiversity
Policy Objectives	Halt decline in, or increase, soil carbon Understand the impacts of policies on changes in total soil carbon and in different soil carbon pools
Source(s)	Draft directive, UN targets
Indicator Assessments	To determine if there have been significant changes in soil organic matter (SOM) across land use types
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Measurement (Indicator Variable(s))	**Carbon pools from TGA-FTIR** SOM (LOI) Soil organic matter, SOC concentration from TC/SOM SBC Soil black carbon (Charcoal) SIC Soil inorganic carbon **Total Carbon content** TC Total carbon
Units (Measured Variable(s))	g SOM/kg oven dry soil g SBC/kg oven dry soil g SIC/kg oven dry soil g TC/kg oven dry soil
Indicator assessment parameter	Mean, standard deviation and upper and lower 95% confidence limits following transformation to normal distribution
Indicator Quantity	Mean status in SOM, SBC, SIC and TC content in specified reporting class e.g. habitat types or soil types.
Reporting unit	Land use: Cropland, grassland, Woodland

	Soil type: WRB classes
Type of result	Is soil mean organic matter content increasing according to previous means?
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	(i) The width of a 95% confidence interval for the true mean SOM (g/kg) uncertainty acceptable to end user, or (ii) The width of a 95% confidence interval for true change in mean SOM, SBC, SIC (g/kg) uncertainty acceptable to end user
Action level required (mean)	NA, no action level identified to date, benchmarking determines context for levels and change in levels.
Assessment interval	Maximum 5-year cycle. SOC levels may decline by as much as 1-2% per year from original level (baseline) with some typical land use conversions.
Soil sampling dimensions	Provides key information about the sampling, single sample, bulk ed sample, width, depth etc. e.g. LUCAS standard 0-20cm deep sample.
Appropriate sampling procedure	LUCAS sampling procedure using volumetric core to ensure bulk density measurement
Analytical method(s)	**Carbon pools from TGA-FTIR (LOI) which removes hygroscopic water first at 105ºC** SOM (LOI) Soil organic matter, SOC concentration from TC/SOM SBC Soil black carbon (Charcoal) SIC Soil inorganic carbon **Total Carbon analyser (thermal oxidation)** TC Total carbon
Archiving	Samples should be archived for future analysis. Air-dried 2 mm sieved soil sample.
Additional information	TGA plus TC provides both calibration and a check on the mass balance of carbon pools. Increases in wildfires and additions of biochar with charcoal may alter the balance of carbon pools over time altering soil health. SIC is there to ensure that TC in soils is assessed; climate change, more rain, and fertilization (making the soil more acidic) may lead to declines in SIC.

	Exploration of other indicators in this channel: O horizon depth by rod, POM and MAOM pools, hot water extractable carbon-biomass proxy.
Efficiency and Cost	Present cost: per sample is low but initial capital investment in equipment needed.
Surrogate Indicators	Soil spectroscopy may assist with these metrics but at present the uncertainty is higher than the laboratory measurements.

Such tables should provide a coherent framework for the development and assessment of indicators including their final presentation. As such, establishing such tables for existing and new indicators may provide a crucial step in ensuring the robustness of the indicator approach for the EU mission and soil monitoring law.

12. Soil Health and its links to the EU Mission: A Soil Deal for Europe

The European Mission: A Soil Deal for Europe implementation plan has set the ambitious approach of moving towards healthy soils within the next decade (EC, 2021). This is because between 60-70% of Europe's soils is currently rated as being "*unhealthy*" leading to unsustainable management, a loss of soil organic carbon (SOC) and threats to biodiversity (Veerman et al., 2020; Feeney et al., 2023). This will also lead to an increase in soil erosion with a likely 60% increase in the next 30 years if current trends continue (Borrelli et al., 2017).

To address these objectives, the Mission has identified eight channels (**Table 2** in the previous section) with indicators that will seek to inform regarding soil performance over time with the policy objective of transitioning towards healthy soils by 2030 and completely sustainable by 2050. The Soil Monitoring Law proposed the establishment of **soil districts** within which monitoring, and assessment should be undertaken. Some considerations on the design of soil districts are provided in **Appendix 2**.

13. Operationalising indicators to address soil health: Ruling in or ruling out?

Soil health is increasingly seen as the current measured condition of a plot, field, region, or area (EC, 2023a). However, based on a diagnostic approach, there are two different ways in which the condition of a soil or its soil health status can be determined to support ecosystem services and initiatives like the Sustainable Development Goals (SDGs) and The Green Deal. In an ideal world, both would be used, however, cost often precludes this.

The first of these relates to a "*ruling in*" approach. 'Ruling in' requires building a case to demonstrate the attribute under consideration. Whilst the approach is holistic, it can also be inefficient with a lot of information required to confirm the attribute. Conversely, "*ruling out"* is a reductionist approach. The soil threat framework proposed by the EU can be used in the context of ruling out and is the current approach of the Joint Research Council (JRC) (Panagos et al., 2024). If a soil is not subject to any of the key soil threats, then, by exclusion, it is considered to have a "*healthy"* status. However, the presence of a single threat would rule it unhealthy. The rule out approach is perhaps more useful in the case of a monitoring framework because decision makers need to understand: (i) if a soil is degraded, and (ii) if policy measures can be implemented to reverse the degradation.

The EU's approach to measuring soil health is to concentrate on soil threats as its basis. This involves an assessment of the soil undertaken to determine the likelihood of the soil being exposed to actual threats that could impact its condition. The SML has documented a particular set of indicators and soil metrics, which have been termed '*descriptors*' and are summarised below.

The main aspects of soil degradation that affect the EU are linked to the following topics:

Aspect of soil degradation	**Descriptors**	**Criteria for healthy soil conditions**	**Excluded Areas**
Salinisation	electrical conductivity (deci-Siemens per meter)	< 4 dS m−1 when using saturated soil paste extract (eEC) measurement method, or equivalent criterion if using another measurement method	Natural saline land areas: land areas affected by sea level rise
Soil erosion	Soil erosion rate, tonnes per hectare per year	(≤ 2 t ha-1 y –1)	Badlands and other unmanaged natural land areas
Soil Organic Carbon Loss	SOC concentration g per kg	Organic soils - respect targets set for such soils at national level in accordance with Article 4.1, 4.2, 9.4 of Regulation (EU)	Non- managed soils in natural land areas

		Mineral soils - SOC/Clay ratio > 1/13)	
Subsoil Compaction	Bulk density in subsoil or equivalent dependant on Member State	In case a Member State replaces the soil descriptor “bulk density in subsoil” with an equivalent parameter, it shall adopt criterion for healthy soil	Non- managed soils in natural land areas

The main aspects of soil degradation that affect the Member States are linked to the following topics:

Aspect of Soil degradation	**Descriptors**	**Excluded Areas**
Excess nutrient content in soil	Extractable phosphorous	No exclusion
Soil contamination	Concentration of heavy metals in soil e.g. As, Sb, Cd etc	No exclusion
Reduction of soil capacity to retain water	Soil water holding capacity of the soil sample as a % of water/volume of saturated soil	No exclusion

The main aspects of soil degradation that have no criteria are linked to the following topics:

Aspect of soil degradation	**Descriptors**
Excess Nutrient Content in Soil	Nitrogen in soil (mg g-1)
Acidification	Soil acidity (pH)
Topsoil compaction	Bulk density in topsoil i.e. A Horizon) (gcm-3)
Loss of soil biodiversity	Such descriptors include soil basal respiration in dry soil as well as bacteria metabarcoding, fungi, nematode abundance and diversity, microbial biomass, earthworm abundance and diversity in cropland

14. Approaches that could be incorporated into AI4SoilHealth

AI4SoilHealth is focused mostly on the large scale and national to pan-EU assessment, however, assessments need to also be interpretable at the field scale. The DPSIR framework provides the foundational basis, linking policy and soils providing the context for soil health assessment to be measured and assessed. Different ways of approaching assessment are described below and in **Figure 2**.

The first approach raises awareness and is based on land uses. It draws on the known linkage between land use and potential degradation by soil threats. Land uses can range from native woodlands, shrublands, grasslands, croplands and many more. A stakeholder could then select the land use of interest to them and from this, they would be able to identify the potential range of threats and impacts by the land use that is selected.

A second approach is to better utilize map products being generated in AI4SoilHealth or by others. For instance, the European Union Soil Observatory (EUSO) website highlights degradation indicators that are mapped. Given the user portal being developed in AI4SoilHealth, a user could select a region of interest and then obtain statistics on the area of healthy soils and the area with one or more threats.

Each of these approaches is used to guide stakeholders to key soil health issues that might be an issue and need dealing with. The next step is to investigate whether there is evidence of these threats. This can be done in several ways.

The first of these is to use a field assessment key to look at how soil can be diagnosed in the field. An example of this is the Soil Health Evaluation, Rating Protocol and Assessment (SHERPA) tool which is currently under development. A different, more technical investigative approach is to carry out traditional specific field sampling and measurements. Some indicators have well defined trigger values in the literature or policy, but some indicators do not and therefore may require a different approach.

An assessment of indicators can be undertaken in different ways. One is to use **threshold or prompt values** which have been identified and agreed upon. Threshold values are normally determined through national policy. Threshold values can be defined as "*values above or below which a significant shift or rapid adverse change takes place*" (Van Lynden et al., 2004; EEA, 2023). This can be a single critical value or the critical limits of a range of values (if the variability of soil conditions so requires)" (Baritz et al., 2021). Thresholds are required within soil health assessments to better inform and examine the extent to which soil functions are degraded.

Trigger values are often used in tandem with thresholds. Trigger values may provide warning or action levels. Warning levels might trigger further investigation, whilst action levels provide a definitive clear limit that if reached requires intervention. These are often available for soil pollutants and heavy metal concentrations. Trigger values can be defined as "*critical limits which inform us of any potential risk to degraded soils and to ecosystems, water and human health*" (EEA, 2023)". A further approach is to use **benchmarks** which refer to indicators where there are no known thresholds currently accepted (e.g., pH, SOM, earthworm counts (Feeney et al., 2023)). Benchmarking is performed based on obtaining the distribution of a population of samples with similar characteristics, such as loam soils under arable cultivation. The population is sampled, usually as part of a national monitoring program, to obtain the distribution. Measurements obtained by a stakeholder can then be compared or benchmarked against the sampled population. Benchmark values can be "*generated from representative datasets which allow for an indicative comparison with regionally representative measured values, but do not allow for a direct evaluation of specific soil functions*" (Bünemann et al., 2018; Verheijen et al., 2005). The challenge with the benchmark approach is that you don't know the state of the population sampled. It may already be highly degraded; thus, the benchmark is only telling the user how their measure compares to others. However, benchmarking is a useful management tool that provides an understanding of where the measurements sit and may guide a stakeholder to look for alternative practices for improvement if it is obvious others are performing better. Moreover, change over time can be observed as monitoring schemes update populations which can prove that the method is useful.

After appropriate investigation, the final stage would be to take required action depending on what soil threats and issues are taking place within certain locations. This can be in the form of national guidance (e.g. policy instruments used within certain countries such as Common Agricultural Policy (CAP)), regional or farming guidance (e.g., soil nutrient health management scheme such as the example used in Northern Ireland (AFBI, 2024 - https://www.afbini.gov.uk/articles/soil-nutrient-health-scheme) , Crap app (Agritech Cornwall, 2024 - https://www.agritechcornwall.co.uk/projects/the-farm-crap-app-pro/) and WOCAT sustainable practices (WOCAT, 2024- https://www.wocat.net/en/) or by including regeneration practices in the relevant national plan as proposed by SML. In this context, relevant national plans can relate to anything from: nature restoration plans under the Nature Restoration Regulation, CAP strategic plans, action programmes under the Nitrates Directive, river basin management plans under the Water Framework Directive, national air pollution control programmes under the NEC Directive, and integrated national energy and climate plans under the Regulation on the Governance of the Energy Union and Climate Action.

Monitoring these actions over a sustained period will be crucial.

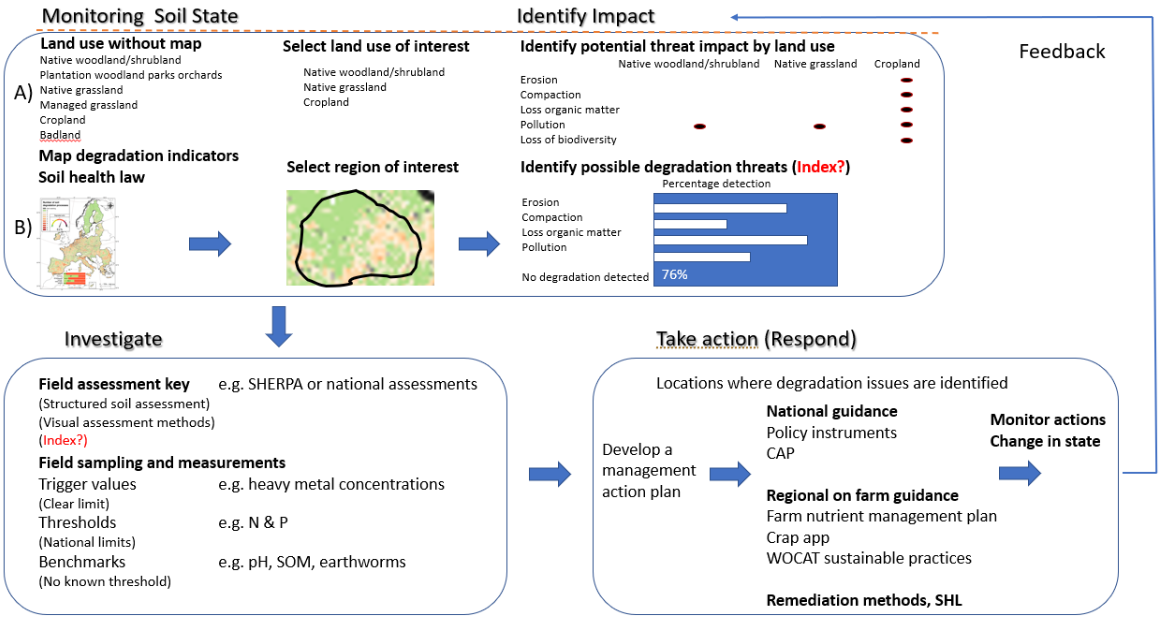


Figure 2: Perceived flowchart for Soil Health Assessment using the DPSIR Action Cycle.

15. Summary

In summary, we have in D3.1 examined and created a recommended selection framework for identifying appropriate Soil Health Indicators. This has been based on a range of policy and stakeholder needs that have been highlighted in this report and in deliverables and tasks within WP2.

This deliverable will provide important guidance and recommendations for facilitating subsequent work in WP4, 5 and 6 as well as provide a robust framework for selecting appropriate SHIs, constructed upon a set of selection criteria. This report has acknowledged that selecting the most appropriate indicators must take the detection of state and change into account as well as making sure that the appropriate indicators provide a range of desired soil ecosystem functions and services to plants, animals and humans.

This report acknowledges the EU Mission Board's objectives and targets set in the Soil Mission Implementation Plan and remains hopeful that a list of appropriate SHIs that filter across one or multiple channels can be further developed and used. The SML as well as future policy and management objectives should help to facilitate this. Based upon the information contained in D3.1, this should set the stage for D3.2, which will investigate new, novel approaches to address issues raised generally across AI4SoilHealth and from this report specifically.

Appendix 1: Review of Soil Health Indicators based on a Literature Review

To address what is currently being discussed and investigated in the literature, a systematic literature review was undertaken to highlight what current soil health indicators are being used. As a basis, papers by Bünemann et al., (2018) and Loveland and Thompson, (2002) were used as a high-level overview and a range of historical and current literature was also examined. The review also considered databases across Europe such as SoilGrids, Land Use/Cover Area frame Survey (LUCAS) and United Kingdom Soil Observatory (UKSO). Finally, other academic institutions and professional organisations were also respected in the review process (e.g., European Joint Partnership (EJP), Joint Nature Conservation Committee (JNCC) and European Union Soil Observatory (EUSO)). In total, 18 items (literature, databases, and policy documents) were considered and assessed and can be found in **Table 1 A1**.

Results

The main SHIs that were found to be consistently considered, discussed, and measured were:

- Bulk density
- Total Organic Matter/Carbon/Labile C and N fractions
- pH
- Nutrients (e.g. Available P) (total, available etc.)
- Cation Exchange Capacity (CEC) (Interpretive metric)
- Microbial Activity/Respiration
- Texture/Coarse fragments (Interpretive metric)
- Microbial Biomass

Table 1 A1: List of soil health indicators in various literature and policy documents and where they sit against the EU Mission Indicator Channels.

Indicators in purple represent most commonly considered indicators from this analysis. Links to EU Mission Statements (A-H) are listed below table.

Numbers 1-18 represent the references used for conducting the literature review and are also listed below table.

Links to EU Mission Indicator Channels	Indicator Physical (P) Chemical (C) Biological (B)	Descriptor Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
E	C	Available K	✓			✓		✓	✓			✓	✓					✓	✓	
E	C	Available N	✓		✓	✓		✓	✓									✓	✓	
E	C	Available P	✓		✓	✓	✓	✓	✓			✓	✓	✓				✓	✓	
E	C	Base Saturation						✓		✓		✓							✓	
D	B	Biodiversity			✓		✓	✓	✓	✓				✓		✓			✓	✓
D	B	Biomass						✓				✓							✓	✓
C	P	Bulk density	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E	C	Carbonate content	✓				✓											✓	✓	

E	C	Cation Exchange Capacity (CEC)	✓	✓		✓		✓		✓		✓			✓	✓	✓	✓	✓	
C	P	Clay characteristics	✓	✓				✓		✓	✓							✓		
D	B	Diseases						✓				✓							✓	
D	B	Earthworms				✓		✓												✓
E	C	Electrical Conductivity	✓			✓		✓	✓			✓	✓						✓	
C	P	Erosion	✓		✓			✓	✓	✓	✓	✓			✓				✓	
E	C	Heavy metals					✓	✓	✓						✓					
C	P	Hydraulic Conductivity				✓			✓		✓	✓							✓	✓
B	C	Labile C and N				✓		✓	✓			✓		✓	✓	✓	✓	✓	✓	✓
F, G, H	P, C, B	Land Use Activity Changes/Crop Yield								✓		✓			✓	✓			✓	
D	B	Microbial Activity/ Respiration					✓	✓	✓	✓		✓		✓	✓	✓	✓		✓	✓

D	B	Microbial Biomass	✓	✓		✓	✓	✓	✓	✓		✓	✓							✓
A	C	Micronutrients				✓	✓	✓				✓							✓	
A	B	N Fixation/ fixing bacteria										✓								
E	B	N mineralisation					✓	✓	✓			✓		✓					✓	✓
D	B	Nematodes						✓												
A	C, B	Nutrients (total, available etc.)	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	
A	C	Organic and inorganic Pollutants			✓			✓		✓					✓					
A	C	Other macronutrients				✓	✓	✓	✓			✓							✓	
E	C	pH	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓
C	P	Porosity				✓		✓	✓		✓	✓							✓	✓
A	C	Sodicity and salinity			✓	✓		✓										✓		

F, G, H	P	Soil depth (profile, horizon, humus horizon etc.)				✓	✓	✓		✓	✓		✓		✓	✓	✓			
D	B	Soil Enzyme activities						✓	✓	✓		✓								
E	C	Soil Moisture								✓					✓					
E	P	Soil temperature				✓					✓	✓	✓		✓				✓	
G	P, C, B	soil type						✓												
C	P	Sorptivity								✓	✓									
C	P	Structural Stability				✓		✓	✓	✓	✓	✓			✓	✓				✓
C	P	Surface characteristics			✓	✓		✓	✓	✓	✓								✓	
D, G	B	Tea Bag decomposition													✓	✓				
C	P	Texture/coarse fragments	✓	✓		✓	✓	✓			✓		✓		✓		✓	✓	✓	
B	C	Total Organic Matter/Carbon	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓

C	P	Water Storage				✓		✓	✓	✓	✓	✓	✓			✓			✓	✓

Indicator Channels

A. Presence of pollutants, excess nutrients, and salts
B. Soil Organic Carbon Stock
C. Soil structure including soil bulk density and absence of soil sealing and erosion.
D. Soil biodiversity
E. Soil nutrients and acidity (pH)
F. Vegetation cover
G. Landscape heterogeneity
H. Forest cover

References

1. LUCAS, 2024: LUCAS: Land Use and Coverage Area frame Survey from Joint Research Centre (JRC), European Soil Data Centre (ESDAC). Accessed from: https://esdac.jrc.ec.europa.eu/projects/lucas. [Last accessed 26th February 2024].
2. SoilGrids, 2024: SoilGrids250m 2.0 - A system for digital soil mapping based on global compilation of soil profile data and environmental layers. Accessed from: https://soilgrids.org/. [Last Accessed 26th February 2024].
3. EUSO, 2024 – European Union Soil Observatory. Accessed from: https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/ [Last accessed 26th February 2024].
4. Bünemann E. K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, L., Geissen, V., Kuyper, T.W., Mader, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., and Brussard, L. 2018: Soil quality — a critical review, Soil Biology and Biochemistry 120, pp.105-125 (https://doi. org/10.1016/j.soilbio.2018.01.030).
5. UKRI, 2024: United Kingdom Soil Observatory (UKSO). Accessed from: https://www.ukso.org/ [Last accessed 26th February 2024].
6. European Joint Programme, 2024: EJP Soil: Science to Policy. Accessed from: https://ejpsoil.eu/science-to-policy [Last accessed 26th February 2024].

7. Valani, G.P., Martíni, A.F., Silva, L.F.S., Bovi, R.C., Cooper, M., 2021: Soil quality assessments in integrated crop–livestock–forest systems: A review. Soil Use Management. 37 (1), pp.22–36. https://doi.org/10.1111/sum.12667.
8. Loveland, P.J., Thompson, T.R.E. 2002: Identification and Development of a Set of National Indicators for Soil Quality. R&D Project P5-053, Report P5-053/02/PR. Environment Agency, Bristol, UK. Available from the Environment Agency R&D Dissemination Centre, C/o WRc, Frankland Road, Swindon, Wilts, SN5 8YF. ISBN 1 85705 667 1.
9. Corstanje, R., Mercer, T. G., Rickson, J. R., Deeks, L. K., Newell-Price, P., Holman, I., Kechavarsi, C., Waine, T. W. 2017: Physical soil quality indicators for monitoring British soils. Solid Earth, 8 (5), pp.1003–1016. https://doi.org/10.5194/se-8-1003-2017.
10. Jian, J., Du, X., and Stewart, R. D. 2020: A database for global soil health assessment. Scientific Data, 7(16), 1-8. https://doi.org/10.1038/s41597-020-0356-3.
11. Doran, J.W., and Safley, M., 1997: Defining and assessing soil health and sustainable productivity. In: Pankhurst, C., Doube, B., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health. CAB International, pp. 1–28.
12. Emmett, B.A, Frogbrook, Z.L., Chamberlain, P.M., Griffiths, R., Pickup, R., Poskitt, J., Reynolds, B., Rowe, E., Rowland, P., Spurgeon, D., Wilson, J., Wood, C.M. 2010: Countryside Survey Technical Report No.03/07.
13. Lehmann, J., Bossio, D.A., Kogel-Knabner, I., Rillig, M.C., 2020: The concept and future prospects of soil health. Nature Reviews Earth & Environment. https://doi.org/10.1038/s43017-020-0080-8.
14. Bongiorno, G. 2020: Novel soil quality indicators for the evaluation of agricultural management practices: a biological perspective. PhD Thesis. Wageningen University and Research.
15. GlobalSoilMap.net, 2015. Specifications Tiered GlobalSoilMap products. Release 2.4.
16. ISRIC, 2024: ISRIC World Soil Information. Accessed from: https://www.isric.org/ [Last accessed 26th February 2024].
17. Stewart, R.D., Jian, J., Gyawali, A.J., Thomason, W.E., Badgley, B.D., Reiter, M.S., and Strickland, M.S. 2018: What we talk about when we talk about soil health. Agricultural and Environmental Letters. Research Letter.
18. Harris M., Hoskins, H., Robinson, A., Hutchison, J., Withers, A., Deeks, L., Harris, Way, J., and Rickson, L., JNCC Report 737: Towards Indicators of Soil Health (Project Report). https://jncc.gov.uk/

Previous works have highlighted indicators which have been used across these categories (Bünemann et al., 2018, Corstanje et al., 2008, Loveland and Thompson, 2002, Jian et al., 2020, Stewart et al., 2018). Based upon a range of literature, bulk density, carbon (total organic carbon, total organic matter and labile C and N) and pH are the most used indicators used to assess soil health. However, there is no optimal or universal set of ideal soil characteristics and despite some soil health indicators having greater relevance than others, their explanation will always be dependent on the context. (Lehmann et al., 2020).

Appendix 1 has examined relationships between each descriptor to each of the eight goals or categories defined by The European Mission: A Soil Deal for Europe Implementation Plan. What should be noted here is that there are many indicators which can overlap into two or multiple indicator channels. Most of the measures that made the top ten are either Tier I or Tier II indicators which is consistent across previous research (Guo, 2021, Harris et al., 2023, Bünemann et al., 2018). These are also consistent largely with the indicators highlighted as important by the SML (EC, 2023a).

However, more and more indicators, particularly biological ones, are coming into fruition due to the changes in the science and the paradigm surrounding SHIs. Therefore, the need for a greater defined challenge criteria is required going forward which will help work alongside D3.1. and D3.2. as well as be used as a foundation across other WPs in AI4SoilHealth (e.g., WP5).

Summary

When reviewing SHIs, it is important to take into consideration some additional thoughts that will provide a basis for appropriate selection and effective measurement across environments. The first of these is related to scale. Different SHIs will have a greater or a lower importance depending on how large the environment is as well as its associated resolution. This is particularly true for SHIs such as Soil Organic Carbon (SOC). It will also be very crucial to consider different land use and land cover types within environments when selecting appropriate SHIs. Some indicators may be more important in different environments than others. Indicators such as SOC are an important indicator in peatland and forestry environments but are perhaps less important in more urban areas. It will be important to distinguish indicators that are purely state focussed against ones that are more connected to change in environments. Many state indicators have uncertainties associated with them which can be so high that their use for looking at changes over time will be redundant. Finally, it will be pivotal when selecting SHIs that the needs of stakeholders (e.g., farmers, land managers, policy makers) are considered so that key questions and problems are addressed.

Appendix 2: Working Roadmap for indicator development

Authors: Campbell, G.A., Robinson, D.A., Shokri, N., Afshar, M., Toth, G., Lehmann, P., Borrelli, P., Taylor, J., Keith, A., Minarik, R., Hengl, T., Maskell, L., Nussbaum, M., Alewell, C., Gupta, S.

Overarching selection templates for the 8 Mission indicators.

This appendix contains exemplars of the use of the indicator selection template for a range of existing and potential indicators grouped under the 8 proposed Mission indicator channels below (**Table 1A3**):

Indicator channels proposed by the Mission board

Table 1A3: Indicator channels proposed by the Mission board

Presence of pollutants, excess nutrients, and salts
Soil Carbon
Soil structure including soil bulk density and absence of soil sealing and erosion.
Soil biodiversity
Soil nutrients and acidity (pH)
Vegetation cover
Landscape heterogeneity
Forest cover
Soil literacy

The templates provide a high-level working framework. Through time they will be refined for individual indicators. For those developing new indicators they provide a framework within which to consider the requirements for a successful potential indicator. The emphasis is how to detect change with the indicator and ensure it is sensitive enough and robust enough to enable reporting now and into the future.

Channel 1: Presence of pollutants, excess nutrients, and salts

Authors: Gergely Toth; Nima Shokir, Mehdi Afshar

Indicator Channel: 1) excess nutrients (mineralizable N and Olsen P)	
Major Functions	food production supporting habitats and biodiversity hydrological system's quality
Policy Objectives	optimise nutrient use / fertilisation protect water (underground and freshwater) resources
Source(s)	draft soil monitoring directive; nitrates directive; scientific proposals, national guidelines
Indicator Assessments	To determine if certain concentrations of soil N and P threatens soil health and related environmental status
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	mineralizable nitrogen in topsoil soluble phosphorus concentration in topsoil
Units (Measured Variable)	C/N mg/kg N in soil (by Kjeldahl method) mg/kg P in soil (by Olsen method) may also be considered: - mg/l NO_3- - kg/ha N in area (topsoil 20 cm)
Indicator Parameter	concentration (N, P), ratio (C/N)
Indicator Quantity	mean and SD status of N and P specified by pedoclimatic zones (soil districts) and land uses
Type of result (Qualitative)	-
Type of result (Quantitative)	Is the area under threat by nutrient pollution increases?
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	To be refined by pedoclimatic zones (soil districts) and land uses C/N $\leq$ 18 – 25 (tolerance level: from 2 to 3) 30-120 mg/kg P (tolerance level: from 10 to 20) may also be considered: 50 mg/l NO_3- in leachate to groundwater 2.5 mg N/l in runoff to surface water

Land use type(s)	cropland, grassland, intensive forestry
Action level required (mean)	1) C/N ≤ 15 2) > 120 mg/kg P example for implementation by pedoclimatic zone (soil districts): Continental/Chernozem a) $CaCO3\% < 1 \rightarrow 80$ mg/kg b) $CaCO3\% > 1 \rightarrow 120$ mg/kg Continental/Haplic Cambisol a) pH < 5.5 → 50 mg/kg b) pH 5.5 – 6.5 → 70 mg/kg c) pH > 5.5 → mg/kg
Soil depth	20 cm
Appropriate sampling procedure	LUCAS sampling procedure
Analytical method(s)	total N by modified Kjeldahl method (ISO 11261:1995) or other standard method supplemented by validated conversion function to express the results in mg/kg by the Kjeldahl method P by Olsen method (ISO 11263:1994) or other standard method supplemented by validated conversion function to express the results in mg/kg by the Olsen method
Archiving	Samples should be archived for future analysis. Air-dried 2 mm sieved soil sample.
Additional information	Leaching of N and loss of P largely depends on soil and climate properties, including rainfall intensities and on land use/land cover. Uniform values (like max 50mg/kg P) for excess levels shall be replaced by values specific by pedoclimatic zones (soil districts).

Channel 2: Soil Carbon

Authors: Pete Smith and David Robinson

Indicator Channel: 2) Soil Carbon (Total Soil Carbon Concentration in Topsoil)	
Major Functions	• Food production • Climate mitigation • Hydrological regulation • Supporting habitats and biodiversity
Policy Objectives	Halt decline in, or increase, soil carbon Understand impacts of policies on changes in total soil carbon and in different soil carbon pools
Source(s)	Draft directive, UN targets
Indicator Assessments	To determine if there have been significant changes in soil organic matter (SOM) across land use types
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	<u>Carbon pools from TGA-FTIR</u> SOM (LOI) Soil organic matter, SOC concentration from TC/SOM SBC Soil black carbon (Charcoal) SIC Soil inorganic carbon <u>Total Carbon content</u> TC Total carbon
Units (Measured Variable)	g SOM/kg oven dry soil g SBC/kg oven dry soil g SIC/kg oven dry soil g TC/kg oven dry soil
Indicator Parameter	Mean, standard deviation and upper and lower 95% confidence limits following transformation to normal distribution
Indicator Quantity	Mean status in SOM, SBC, SIC, TC content in specified agricultural land uses or soil types.
Type of result (Qualitative)	Quantitative: Is soil organic matter content significantly different to previous estimates?
Type of result (Quantitative)	Qualitative: Is soil organic matter content increasing according to benchmarks for land use types?
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	(i) The width of a 95% confidence interval for the true mean SOM (g/kg) uncertainty acceptable to end user, or

	(ii) The width of a 95% confidence interval for true change in mean SOM, SBC, SIC (g/kg) uncertainty acceptable to end user
Land use type(s)	All land use types
Action level required (mean)	NA, no action level identified to date, benchmarking determines context for levels and change in levels.
Soil depth	LUCAS standard 0-20cm
Appropriate sampling procedure	LUCAS sampling procedure using volumetric core to ensure bulk density measurement
Analytical method(s)	<u>Carbon pools from TGA-FTIR (LOI) which removes hygroscopic water first at 105^{o}C</u> SOM (LOI) Soil organic matter, SOC concentration from TC/SOM SBC Soil black carbon (Charcoal) SIC Soil inorganic carbon <u>Total Carbon analyser (DUMAS)</u> TC Total carbon
Archiving	Samples should be archived for future analysis. Air-dried 2 mm sieved soil sample.
Additional information	TGA plus TC provides both calibration and a check on mass balance of carbon pools. Increases of wildfires and additions of biochar with charcoal may alter the balance of carbon pools over time altering soil health. SIC is there to ensure that TC in soils is assessed; climate change, more rain, and fertilization (making the soil more acidic) may lead to declines in SIC. Exploration of other descriptors in this channel: O horizon depth by rod, POM and MAOM pools, hot water extractable carbon-biomass proxy.

Channel 3: Soil structure including soil bulk density and absence of soil sealing and erosion

Authors: Peter Lehmann, Pasquale Borrelli, Christine Alewell, Surya Gupta

3.1. Indicator Channel Soil Structure – Ponding time

Scientific background and motivation

Ponding caused by limiting infiltration capacity hinders soil aeration, increases soil erosion rates, and causes severe soil damage if management and construction work is not stopped. The occurrence of ponding depends on soil hydraulic properties (that are dependent on soil structure, soil texture, bulk density, and root distribution), rainfall rate duration, and water content profile and onset of rainfall. To quantify the occurrence and risk of ponding, we use the concept of 'ponding time,' describing the time since onset of the rainfall until water starts to pond on the surface (a 'healthy' soil has thus a large ponding time, an 'unhealthy' soil a short ponding time). We differentiate between the 'actual ponding time' when ponding occurs, and the 'potential ponding time' as soil hydraulic property (for each rainfall intensity, the potential ponding time can be calculated as function of the soil hydraulic properties).

In the project, we invest in collecting information on 'actual ponding time' by developing a mobile phone app. In addition, we evaluate if actual ponding can be deduced from remote sensing signatures (surface reflectance, microwave-based) and from data obtained with soil moisture profile, gamma radiation, and cosmic-ray neutron sensors. However, to estimate the ponding time and its change with seasons and land management at various scales (including Pan-European scale), we will quantify the potential ponding time. This includes measurement of infiltration rate capacities at pilot sites and the estimation of soil hydraulic properties at continental scale. To define the soil health index related to the ponding time, we define for each Land Use/Soil Class reference states for 'unhealthy' and 'healthy' soils, respectively.

As first reference state ('unhealthy soil') we express the ponding time as a function of soil texture (time TT, as texture-defined time). For healthy soils with structural pores enabling fast infiltration, we calculate the ponding time as function of bulk density, ratio of clay and organic content, and biomass as proxy of root properties (time ST, for structure-defined time). The ponding time of a site PT can then be scaled by TT and ST to define a ponding time index between 0 and 1. In addition, a proposal for an 'alarm value' to classify between 'healthy' and 'unhealthy soils' must be developed.

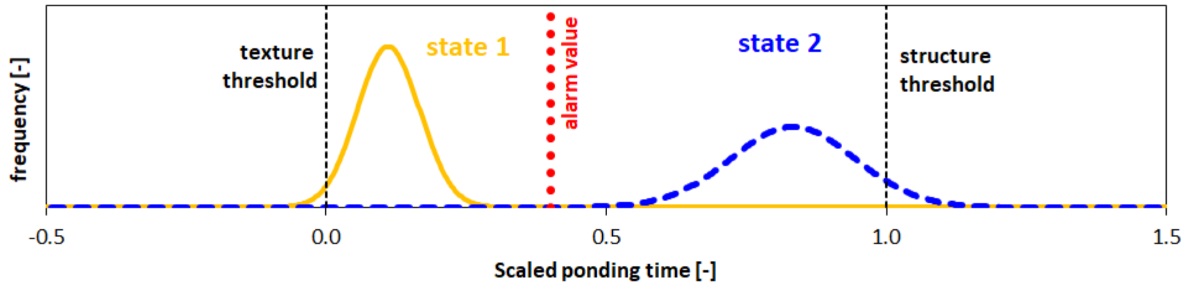


Figure: Conceptual picture of the change in ponding type distribution for a certain LandUse/SoilType from state 1 to state 2. The ponding time values (in hours) PT are scaled by (PD-TT)/(ST-TT) with threshold calculated based on texture (TT) and structural properties (ST), respectively. The 'alarm value' marking the threshold between 'healthy' and 'unhealthy' soil is here set to 0.4 as example.

Soil erosion and compaction are important indicators that continue being developed by JRC and P. Borrelli.

Indicator Channel: 3) Soil Structure 3.1. Change of ponding time	
Major Functions	Flood regulation Crop production Climate Regulation
Policy Objectives	Reducing stagnant water Reducing erosion Reducing flooding Preventing ponding
Source(s)	-
Indicator Assessments	Is the ponding time close to values representative for soils with well-developed soil structures? Is the calculated ponding time larger than the duration of intense rainfall events?
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm, NUTS 3 (districts), Pan EU
Units (Indicator Variable)	Time [hours]
Units (Measured Variable)	Infiltration rate [mm/hour]
Indicator Parameter	Mean, standard deviation and upper and lower 95% confidence limits of scaled ponding time
Indicator Quantity	Ponding time distribution for a specified LandUse/SoilType unit
Type of result (Qualitative)	Is there a trend to larger ponding time values for a certain LandUse/SoilType unit?
Type of result (Quantitative)	Is there a significant increase of ponding time for a certain LandUse/SoilType? What is the scaled ponding time value?

Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	(i) The mean scaled ponding time value (including standard deviation) for a certain LandUse/SoilType must be larger than the critical limit (alarm value) (ii) The change in scaled ponding time must be significantly larger than 0 for soils below the alarm value
Land use type(s)	All land use types
Action level required (mean)	To be defined in the project (for example larger than 0.4)
Soil depth	LUCAS standard 0-20 cm
Appropriate sampling procedure	Beerkan method for infiltration
Analytical method(s)	Standard methods for soil hydraulic properties and bulk density
Archiving	-
Additional information	The ponding time will be calculated for the pilot sites based on hydraulic properties deduced from infiltration experiments

3.2. Indicator Channel Soil Structure – VESS Score indicator

(Primary use with stakeholders for field-based assessment)

Scientific background and motivation

The presence of soil structures enabling fast water infiltration (suppressing erosion) and fast drainage (preventing anaerobic conditions) can be revealed in CT images, deduced from shrinkage and water retention curves, and estimated based on content of clay and organic material. As shown by Johannes (2016), these metrics can be linked quantitatively to the score obtained with the visual evaluation of soil structure quality (VESS). This quantitative field spade test framework allows to define target and remediation values and the quantification of changes with time (and change in management). The light version of VESS (VESS2020) can easily be conducted in the field by farmers and scientists. The estimation of the VESS-Score is thus an integral measure of soil structural properties and should complement standard physical/chemical/biological characterization of soil health.

Within AI4SoilHealth, we intend to show how this VESS-Score value is related (i) to macropore continuity, soil hydraulic properties and land use (PhD thesis Niklas Schmücker), (ii) to shrinkage, clay content and soil organic matter (master thesis Léonie Messmer) to allow (iii) its estimation at PAN European scale as function of soil hydraulic properties, clay content, SOC, and bulk density (University of Basel). The method may be adapted for forest soils and would be an important input to the soil structure mapping needed within the SHERPA framework.

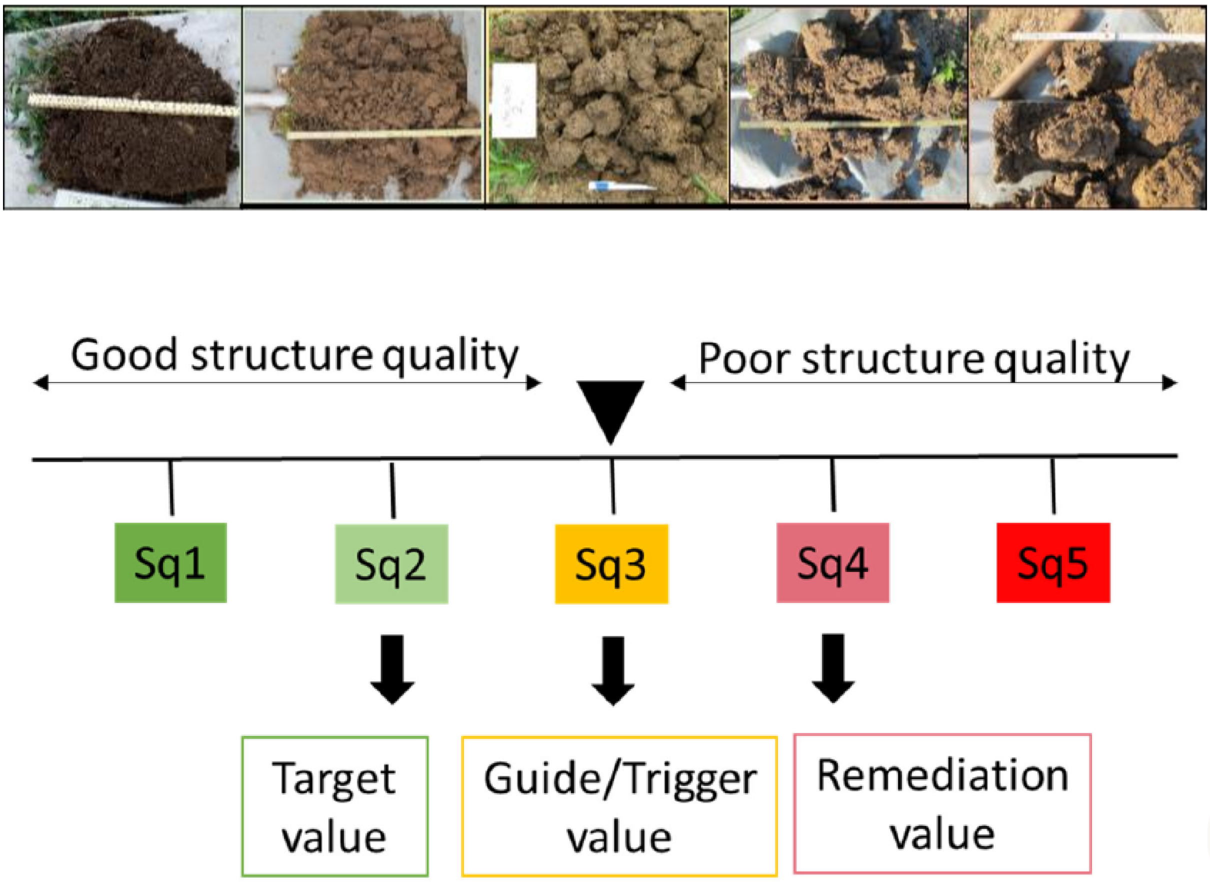


Figure: Assessment of soil structure score value Sq and related thresholds from STRUDEL (2021) with illustrative samples on top (VESS2020). The lower the Sq value, the better is the soil structural quality.

Indicator Channel: 3) Soil Structure 3.2. VESS-Score (Visual Estimation of Soil Structure Score)	
Major Functions	Flood regulation (water storage and infiltration) Water purification (filtering) Climate regulation Carbon sequestration Habitats for organism (biodiversity)
Policy Objectives	Understand impacts of policies with respect to land management on soil structural properties
Source(s)	VES_{2020} and STRUDEL/Agroscope
Indicator Assessments	To determine if the structure score improved (towards lower values) over time for a certain LandUse/SoilType
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm, Pan EU
Units (Indicator Variable)	Sq Score (number between 1 and 5)
Units (Measured Variable)	Aggregate size [mm] Aggregate shape and structure [-] Root presence [-] Colour [-]
Indicator Parameter	Mean, standard deviation and upper and lower 95% confidence limits (for reference season)
Indicator Quantity	Mean status Sq_{mean} in specified LandUse/SoilType
Type of result (Qualitative)	Is Sq_{mean} improving for a certain LandUse/SoilType unit?
Type of result (Quantitative)	Is Sq_{mean} significantly different from previous estimate for a certain LandUse/SoilType unit?
Tolerance Level (Critical Limit, Base Value)	(i) Sq_{mean} is below SQ=3 (Trigger value) for certain LandUse/SoilType (ii) Soil with SQ > 3 improved their grade by 0.25 units
Land use type(s)	All land use types
Action level required (mean)	Sq=4 considered as remediation value with immediate action required
Soil depth	LUCAS standard 0-20cm

Appropriate sampling procedure	Structure assessment in the field
Analytical method(s)	Field assessment
Archiving	Images and protocols are stored
Additional information	The VESS should be assessed at the pilot sites AI4SoilHealth establishes links between VESS and other soil parameters to provide PAN European mapping

3.3. Indicator Channel: Soil Erosion - Lateral Mobilization of Soil

Scientific background and motivation

Soil erosion is among the eight soil threats listed within the Soil Thematic Strategy of the European Commission (COM (2002)179). Soil erosion reduces soil stability, alters soil structures, impedes soil biology, reduces water holding capacity, leads to a loss of soil nutrients and potentially reduces soil organic carbon pools, therefore impairing all major functions of soil, not only its productivity. In addition, off-site effects include major threats to fresh- and ocean waters due to contamination, eutrophication and riverbed clogging as well as considerable damages to infra structure. The ephemeral nature of erosion makes prediction and monitoring to allow for a proper risk assessment and policy mitigation quite challenging. Worldwide, very few national survey programs of soil erosion exist (for example, US National Resources Inventory and Chinese National General Survey Program on Soil and Water Conservation). No coordinated monitoring exists across the European Union. Therefore, innovative systems to modelling and monitoring the soil erosion risk are paramount to support policy and land management strategies.

A major change in soil erosion assessment can only take place when predicting approaches will be able to adequately represent the spatio-temporal dynamics and intra-annual variability of land use, including a spatially explicit indication of the actual cropland use, crop system, and specific application of management practices (e.g., conservation tillage, contour ploughing, crop rotation, cover cropping and mulching, grassed waterways, and buffer strips). In the project Artificial Intelligence 4 soil health, soil erosion will be addressed at pan-European scale aiming at relating soil erosion estimates to the soil stock, economical value of the crops, and nutritional value of the crops. In one of the soil erosion pilot sites (i.e., Rome, Italy), the potential for developing a LPIS-based soil erosion monitoring system will be assessed.

Indicator Channel: 3) Soil Structure 3.3) Soil Erosion (Lateral Mobilization of Soil)	
Major Functions of Soil Erosion Control	Food production Climate mitigation Hydrological regulation Soil pollution control Biogeochemical cycling Freshwater and coastal water quality Supporting habitats and biodiversity
Policy Objectives	Reduce soil erosion and land-river-ocean sediment transfer Understand impacts of policies on the mitigation of soil loss by soil erosion for preserving soil fertility and reduce the total sediment, carbon, pollutant, and nutrient fluxes
Source(s)	Draft directive, UN targets
Indicator Assessments	To estimate the potential total (multi process) on-site soil erosion potential in relation with the available soil stock, crop economic value, and nutritive value of crop.
Domain of interest:	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	Mass [tones], area [hectares], time [years] - [tones/hectares/year]
Units (Measured Variable)	[tones/hectares/event]
Indicator Parameter	Ranking Score
Indicator Quantity	Mean status and temporal changes
Type of result (Qualitative)	NA
Type of result (Quantitative)	Are there a significant difference of soil erosion estimates in agricultural area of different EU countries, bioclimatic regions and soil districts?
Tolerance Level (Critical Limit)	2 tones/hectares/year
Land use type(s)	All land use types
Action level required (mean)	To be defined
Soil depth	Topsoil
Appropriate sampling procedure	UAV LiDAR scanning
Analytical method(s)	NA
Archiving	NA
Additional information	Soil erosion by water will be estimated using a pan-EU GIS-based soil loss prediction model. In the pilot testing site (i.e., Rome, Italy) a LiDAR sensor mounted on a UAV will be used for modelling validation purposes.

Channel 4: Soil biodiversity

Authors: Joe Taylor and Aidan Keith

Indicator Channel: 4) Soil biodiversity	
Major Functions	Recycling of organic matter (Earthworms) Importance in maintaining soil structure (Earthworms and microbes) Major role in cycling of N&P Symbiotic interactions with crop plants- mycorrhizal fungi Production and cycling of greenhouse gases (Methanotrophs/methanogens)
Policy Objectives	Reducing need to OM addition Reducing need for fertiliser application Net zero- reduction in greenhouse gas flux
Source(s)	
Indicator Assessments	To identify useful bioindicators of soil nutrient conditions and useful metrics of diversity/richness that are indicative of soil health status
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	Direct counts- earthworms/meiofauna eDNA/sequence data
Units (Measured Variable)	Earthworm density Earthworm species Mesofauna counts Bioindicator taxa (Bacteria, Protists Fungi) for nutrient conditions/ soil health. • Richness of bacteria • Shannon of bacteria • Richness of fungi • Shannon of fungi • Bacterial chemoheterotrophs • Bacterial N-fixers • Bacterial human pathogens • Ectomycorrhizal fungi • Arbuscular mycorrhizal fungi • Fungal saprotrophs • Fungal plant pathogens Community dissimilarity
Indicator Parameter	
Indicator Quantity	Mean values of metrics- modelled to soil health/nutrient status
Type of result (Qualitative)	Relative abundance
Type of result (Quantitative)	Numbers of taxa, counts of mesofauna

Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	Unknown at this stage
Land use type(s)	cropland, grassland, intensive forestry
Action level required (mean)	Unknown at this stage
Soil depth	20 cm
Appropriate sampling procedure	LUCAS sampling procedure
Analytical method(s)	Earthworm surveys DNA metabarcoding for Bacteria and Eukaryotes
Archiving	Samples should be archived for future analysis. Air-dried 2 mm sieved soil sample. Frozen soils. DNA sequence data archived on the NCBI sequence reads archive
Additional information	

Channel 5: Soil nutrients and acidity (pH)

Authors: Robert Minarik and Tomislav Hengl (with contributions from Gergely Toth)

Indicator Channel: 5) Soil nutrients and acidity (pH)	
Major Functions	food production agricultural land use monitoring
Policy Objectives	optimise nutrient use / fertilisation sustainable agriculture energy efficiency targets
Source(s)	draft soil monitoring directive: scientific papers related to the soil health
Indicator Assessments	To select close to nature (not intensively managed)/natural soils in the same soil district sharing the same land use (and soil type) for getting common distributions of soil nutrients (etalon). To compare the values of the soil samples and their position in the relevant etalon distributions to detect the health status of the soil. The health status should be assessed based on the most limiting factor not the mean.
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	All scales
Units (Indicator Variable)	**Macronutrients:** **Total Nitrogen** (channel 1 overlap) & Available Nitrogen **Total & Available Phosphorus** (channel 1 overlap) Total **& Available Potassium** Total Calcium Total & Available Magnesium Total Sulphur **Micronutrients:** Copper

	Zinc Cobalt - important in grasslands **Ratios:** C:N ratio change (overlap with the channel 1) [N, P, K | Ca, Mg] [N, P | K] [N | P] [Ca | Mg] **Soil pH in water and CaCl2** **Cation exchange capacity**
Units (Measured Variable)	mg/kg: P; K; Mg, S, Cu, Zn, Co g/kg: N; Ca pH: unitless
Indicator Parameter	concentration of nutrients, ratios
Indicator Quantity	statistics of the distribution
Type of result (Qualitative)	To be developed in the project: Soil health index??
Type of result (Quantitative)	Absolute levels/ratios of nutrients and pH in the soil as input info for the management purposes
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	Based on the distributions/To be developed in the project
Land use type(s)	Agricultural land (arable land, grasslands, agroforestry)
Action level required (mean)	
Soil depth	0-20 and 20-50
Appropriate sampling procedure	LUCAS protocol
Analytical method(s)	N: ISO 11261:1995

	P, Ca, Mg: ISO 11263. 1994 K: USDA, 2004 Atomic absorption spectrometry after extraction with NH4OAc Cu, Zn, Co: 11047:1998 Soil pH: ISO 10390:2005 other standard method supplemented by validated conversion functions to ISO standards
Archiving	
Additional information	It would be great to relate the nutrient with the yield to detect limiting factors. It would help to prevent overfertilisation of the soil when there is another limiting factor

Channel 6: Vegetation cover

Authors: Robert Minarik and Tomislav Hengl (with contributions from Gergely Toth)

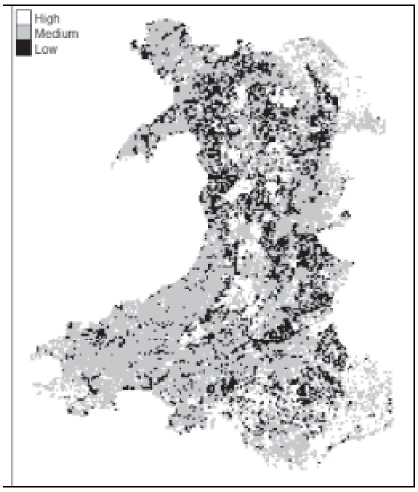
Indicator Channel: 6) Vegetation cover	
Major Functions	Vegetation is the primary soil ecosystem service i.e. it ensures primary production of biomass and protection of soil from degradation (soil erosion, wind erosion and similar).
Policy Objectives	Continuous vegetation cover / continuous ecosystem functions ensure that the soil is protected from erosion and that primary ecosystem services are fulfilled, especially the primary productivity through photosynthesis.
Source(s)	draft soil monitoring directive: scientific papers related to the soil health and vegetation monitoring
Indicator Assessments	To ensure that there is continuous vegetation cover also in different seasons and that the vegetation is health i.e. not suffering from droughts, fires or similar;
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	All scales
Units (Indicator Variable)	**Biophysical variables:** - Monthly Gross Primary Productivity. - Normalized Difference Tillage Index (NDTI). - Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). - Loss of peatlands and wetlands (land cover change). - Canopy height (forest tree canopy from GLAD). - Canopy biomass density (t/ha). - Land Use and Land Cover change.
Units (Measured Variable)	GPP in kg/ha/day; fraction of vegetation cover; vegetation height in m. fraction of photosynthetically active radiation; land cover classes based on the Corine Land Cover classification (CLC)
Indicator Parameter	

Indicator Quantity	various
Type of result (Qualitative)	land cover changes indicating degradation or land in terms of deforestation, urbanization/sealing, removal of wetlands and similar
Type of result (Quantitative)	vegetation height in m (to distinguish forests from open areas / grasslands and croplands).
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	Based on the distributions/To be developed in the project
Land use type(s)	Agricultural, forest area, grasslands, protected areas / nature parks and similar
Action level required (mean)	
Soil depth	NA
Appropriate sampling procedure	
Analytical method(s)	other standard method supplemented by validated conversion functions to ISO standards
Archiving	
Additional information	These are not really soil variables but should be considered auxiliary soil variables.

Channel 7: Landscape Heterogeneity

Authors: Lindsay Maskell and David Robinson

Indicator Channel: 7) Landscape Heterogeneity	
Major Functions	• Food production • Climate mitigation • Hydrological regulation • Supporting habitats and biodiversity
Policy Objectives	Protect nature and reverse the degradation of ecosystems by restoring ecosystems, habitats and species. Increase the share of agricultural land with high-diversity landscape features. Support the quality of landscapes, preserving cultural heritage and greening towns and cities. Prevent soil erosion, improve soil structure, conserve and increase soil carbon stocks. Explore potential for the soil functional (micro)biome to deliver improved soil health and associated ecosystem services with a focus on non-agricultural soils.
Source(s)	EU Biodiversity strategy and nature restoration law, Farm to fork. EU mission soils
Indicator Assessments	To determine changes in landscape heterogeneity and relationships to soil health
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	Diversity of landscape elements (composition) and configuration (size and location). Elements include. • on farmland- field size, fragmentation, presence of natural green elements (field margins, hedgerows) • forestry (types of forest, monocultures, clear-cuts with bare land) link to forestry cover indicator • urban green infrastructures (adequate presence). • Habitat diversity Will also explore using HNV farming as a surrogate measure
Units (Measured Variable)	Composite measure of landscape heterogeneity incorporating above elements.
Indicator Parameter	Indicator score benchmarked through analysis
Indicator Quantity	Indicator score in specified agricultural land uses or soil types.
Type of result (Qualitative)	What are the relationships between Landscape heterogeneity and soil quality e.g. SOC, soil biodiversity

Type of result (Quantitative)	What is the current state of landscape heterogeneity across the EU? How does that impact soil quality e.g. SOC, soil biodiversity
Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	NA, indicator will be developed in relation to benchmarks of landscape heterogeneity in context
Land use type(s)	All- semi-natural, agricultural, forest
Action level required (mean)	NA, no action level identified to date
Soil depth	NA
Appropriate sampling procedure	Indicator derived from remotely sensed data
Analytical method(s)	Multi-variate analysis, linear mixed models, random forest models predicting soil vars from heterogeneity.
Archiving	NA
Additional information	Demonstrating proof of concept using national fine-scaled data. Previous work created a Heterogeneity index (HNV type 2), but more work required to relate to soil properties e.g. soil type diversity, soil biota, soil carbon, bulk density, soil erosion.  Then need to scale to EU using remote sensing datasets e.g. Copernicus Programme, woody cover 3m resolution, Corine, Land cover mapping within Eco Datacube. We will explore HNV maps and how they relate to other remotely sensed data and check out global heterogeneity data. Re-analyse relationships between landscape heterogeneity and soils using LUCAS (Land Use Change Analysis System), EU Soil Observatory, SoilGrids, Field survey data.

Channel 8: Forest Cover

Authors: Lindsay Maskell and David Robinson

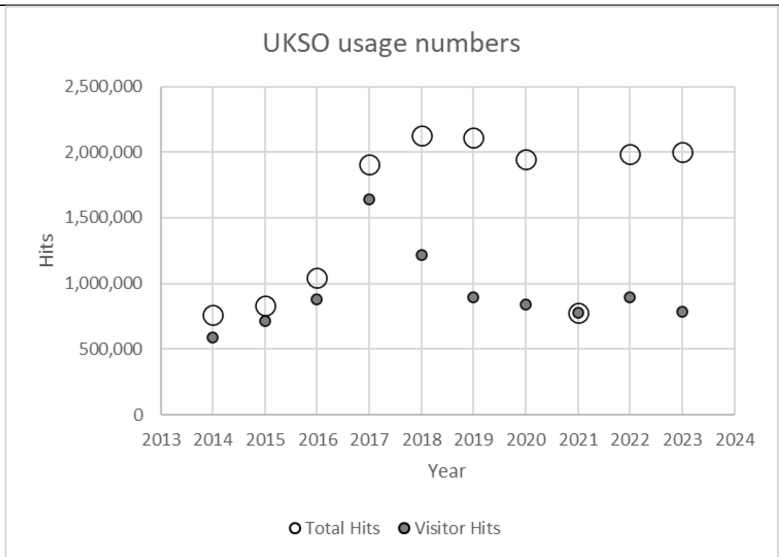
Indicator Channel: 8) Forest Cover	
Major Functions	• Timber production • Climate mitigation • Hydrological regulation • Supporting habitats and biodiversity
Policy Objectives	Protect nature and reverse the degradation of ecosystems (including desertification). Improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience. Adapt Europe's forests to the new conditions, weather extremes and high uncertainty brought about by climate change. Prevent soil erosion, improve soil structure, conserve and increase soil carbon stocks.
Source(s)	EU forest strategy; EU biodiversity strategy, EU mission soils
Indicator Assessments	To determine how forest cover relates to soil health and how soil health influences forest cover.
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	Farm scale, NUTS1, NUTS0, Pan EU
Units (Indicator Variable)	• 'Naturalness' - Species richness/composition (may not be possible) - Evergreen and deciduous area change - Plantation vs native area change (include ancient woodland/orchards) - Management e.g. clear felling - Canopy structure - Deadwood - Productivity NDVI/GRVI • Shape and size- area; perimeter ratio, mean patch area, connectivity • Canopy gaps / disease
Units (Measured Variable)	Area of different types of forest cover m/km2
Indicator Parameter	Mean, standard deviation and upper and lower 95% confidence limits
Indicator Quantity	Mean status in different landscape types.
Type of result (Qualitative)	
Type of result (Quantitative)	Is the area of 'natural forest' increasing? How does this relate to soil carbon/soil structure? Is the area of canopy gaps changing (possibly created by disease)- what implications does this have for soil health?

Tolerance Level (Critical Limit, Base Value) **(d: tolerance level)**	(i) The width of a 95% confidence interval for the true mean by landscape context (ii) The width of a 95% confidence interval for true change in mean by landscape context
Land use type(s)	Forest cover across all landscapes
Action level required (mean)	NA, no action level identified to date, benchmarking determines context for levels and change in levels
Soil depth	NA
Appropriate sampling procedure	NA
Analytical method(s)	
Archiving	
Additional information	Fionas work? Potential EU datasets woody cover 3m resolution

Channel 9: Soil Literacy (web-based analytics)

Authors: David Robinson

Indicator Channel: 9) Soil Literacy (Web based analytics)	
Major Functions	• Food production • Climate mitigation • Hydrological regulation • Supporting habitats and biodiversity
Policy Objectives	Understand the scale of the stakeholder community and soil data usage.
Source(s)	EU Mission on soil health and food
Indicator Assessments	To determine if soil data is accessed by the public
Domain of interest: Farm scale, NUTS1, NUTS0, Pan EU	NUTS 0 and Pan EU
Units (Indicator Variable)	Hits on a website
Units (Measured Variable)	Number of total hits on a site annually Number of unique visitor hits on a site annually
Indicator Parameter	Count
Indicator Quantity	Count per country or EUSO
Type of result (Qualitative)	Quantitative: Is the number of visitors to soils information increasing across the EU?
Type of result (Quantitative)	NA
Tolerance Level (Critical Limit, Base Value) (d: tolerance level)	NA
Land use type(s)	NA
Action level required (mean)	NA
Soil depth	NA
Appropriate sampling procedure	Records from website analytics
Analytical method(s)	Website analytics
Archiving	NA
Additional information	An example of the annual user counts from the UK Sol Observatory partners over the last decade.



‘Tolerance levels’ are the standard error, confidence intervals, error variance etc. (From Black et al., 2008).

Action level or critical limit known

Determine whether an indicator deviates significantly from an action level. *For example, for the risk characterisation ratio of copper, the estimated RCR of permanent grassland in Wales is 1.2 (example only) with 95 per cent confidence that this value obtained from monitoring is significantly different to 1 (which is the action-level). In this instance, the tolerance interval would be defined for the indicator value at the 95 per cent confidence level.*

Action level or critical limit unknown

Description of an indicator’s mean, standard deviation and upper and lower 95 confidence limits for the relevant reporting classes following transformation to normal distribution. *For example, for SOC, the mean value of carbon for a particular land use within England is estimated as 20 g kg^{-1} with 95 per cent confidence that the true value of the mean lies between 18 and 22 g kg^{-1}. The tolerance interval in this instance has been set at ±2 g kg^{-1} (for illustration only)*

Determine the significance of any change in an indicator for the relevant reporting classes from previous samplings. *For example, for SOC, the estimated change for a particular land use over 10 years is 2 g kg^{-1} with a 95 per cent confidence that the change is significantly different to zero. In this instance, the tolerance interval has been given as 2 g kg^{-1}*

(for illustration only).

References

AFBI, 2024: Soil Nutrient Health Scheme. Accessed from: https://www.afbini.gov.uk/articles/soil-nutrient-health-scheme. [Last accessed 23rd February 2024].

Agritech Cornwall, 2024: The Farm Crap App Pro. Accessed from: https://www.agritechcornwall.co.uk/projects/the-farm-crap-app-pro/. [Last accessed 23rd February 2024].

Arshad, M. A. and Martin, S., 2002: Identifying critical limits for soil quality indicators in agro ecosystem, Agriculture, Ecosystems & Environment 88, pp. 153-160 (https://doi.org/10.1016/S0167-8809(01)00252-3).

Baritz, R., Amelung, W., Antoni, V., Boardman, J., Horn, R., Prokop, G., Römbke, J., Romkens, P., Steinhoff-Knopp, B., Swartjes, F., Trombetti, M., de Vries, W. 2021: Soil monitoring in Europe: Indicators and thresholds for soil quality assessments. EEA ETC/ULS Report | 2021.

Bethel, J. 1989: Sample Allocation in Multivariate Surveys. Survey Methodology 15: pp. 47–57.

Black, H., Bellamy, P., Creamer, R., Elston, D., Emmett, B., Frogbrook, Z., Hudson, G., Jordan, C., Lark, M., Lilly, A. and Marchant, B., 2008: Design and operation of a UK soil monitoring network.

Bone, J., Barraclough, D., Eggleton, P., Head, M., Jones, D.T., Voulvoulis, N., 2014. Prioritising soil quality assessment through the screening of sites: the use of publicly collected data. Land Degradation & Development 25, pp. 251–266.

Bonfante, A., Basile, A., and Bouma, J. 2020: Targeting the soil quality and soil health concepts when aiming for the United Nations Sustainable Development Goals and the EU Green Deal, Soil 6, pp. 453-466 (https://doi.org/10.5194/soil-6-453-2020).

Bongiorno, G. 2020: Novel soil quality indicators for the evaluation of agricultural management practices: a biological perspective. PhD Thesis. Wageningen University and Research.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schutt, B., Ferro, V., Bagarello, V., Van Oost, K., Montanarella, L., and Panagos, P. 2017: An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications, 8, https://doi.org/10.1038/s41467-017-02142-7.

Brevik, E.C. 2018: A brief history of the soil health concept. The Soil Science Society of America. https://profile.soils.org/files/soil-communication/documents/95_document1_d50a8524-dbf4-4856-8c62-4a03ede6c3d4.pdf.

Brus, D.J. 2023: Spatial Sampling with R. Accessed from: https://dickbrus.github.io/SpatialSamplingwithR/ [Last accessed 23rd February 2024].

Bünemann E. K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, L., Geissen, V., Kuyper, T.W., Mader, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., and Brussard, L. 2018: Soil quality — a critical review, Soil Biology and Biochemistry 120, pp.105-125 (https://doi. org/10.1016/j.soilbio.2018.01.030).

Copernicus 2024: CORINE Land Cover. Accessed from: https://land.copernicus.eu/en/products/corine-land-cover [Last Accessed 22nd February 2024].

Corstanje, R., Mercer, T. G., Rickson, J. R., Deeks, L. K., Newell-Price, P., Holman, I., Kechavarsi, C., Waine, T. W. 2017: Physical soil quality indicators for monitoring British soils. Solid Earth, 8 (5), pp.1003–1016. https://doi.org/10.5194/se-8-1003-2017.

Doran J. W., 2002: Soil health and global sustainability: translating science into practice, Agriculture, Ecosystems & Environment 88, pp. 119-127.

Doran, J.W., and Parkin, T.B., 1996: Quantitative indicators of soil quality: a minimum data set. In: Doran, J.W., Jones, A.J. (Eds.), *Methods for Assessing Soil Quality*. Soil Science. Society of America, Special Publication 49, Madison, WI, pp. 25–37.

Doran, J.W., and Safley, M., 1997: Defining and assessing soil health and sustainable productivity. In: Pankhurst, C., Doube, B., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health. CAB International, pp. 1–28.

Emmett, B.A, Frogbrook, Z.L., Chamberlain, P.M., Griffiths, R., Pickup, R., Poskitt, J., Reynolds, B., Rowe, E., Rowland, P., Spurgeon, D., Wilson, J., Wood, C.M. 2010: Countryside Survey Technical Report No.03/07.

European Commission, 2006: Thematic Strategy for Soil Protection. Commission of the European Communities, pp. 12.

European Commission, 2023a: Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law). Brussels, 5.7.2023. COM (2023) 416 final. 2023/0232 (COD).

European Commission, 2023b: European Missions: A Soil Deal for Europe - 100 living labs and lighthouses to lead the transition towards healthy soils by 2030. Implementation Plan.

European Environmental Agency, 2023: Soil Monitoring in Europe – Indicators and thresholds for soil health assessments. EEA Report. No 08/2022.

European Joint Programme, 2024: EJP Soil: Science to Policy. Accessed from: https://ejpsoil.eu/science-to-policy [Last accessed 26th February 2024].

EUSO, 2024 – European Union Soil Observatory. Accessed from: https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/ [Last accessed 26th February 2024].

Faber, J.H., I. Cousin, K.H.E. Meurer, C.M.J. Hendriks, A. Bispo, M. Viketoft, L. ten Damme, D. Montagne, M.C. Hanegraaf, A. Gillikin, P. Kuikman, G. Obiang-Ndong, J. Bengtsson, A.R. Taylor., 2022: Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values. EJP SOIL Internal Project SIREN, Deliverable 2. Report, 153 pp. Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values (SIREN) (wur.nl).

FAO 2024: FAO Soils Portal. Accessed from: https://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/ [Last accessed 23rd February].

FAO and ITPS. 2015: Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

Feeney, C. J., Robinson, D. A., Keith, A. M., Vigier, A., Bentley, L., Smith, R. P., Garbutt, A., Maskell, L. C., Norton, L., Wood, C. M., Cosby, B. J., & Emmett, B. A. 2023: Development of soil health benchmarks for managed and semi-natural landscapes. Science of The Total Environment, 886, 163973. https://doi.org/10.1016/J.SCITOTENV.2023.163973.

Gabrielsen P., and Bosch P. 2003: Environmental Indicators: Typology and Use in Reporting European Environment Agency: Copenhagen, Denmark.

Giupponi, C., and Vladimirova, I., 2006: Ag-PIE: a GIS-based screening model for assessing agricultural pressures and impacts on water quality on a European scale. Science of the Total Environment 359 (1–3), pp. 57–75.

GlobalSoilMap.net, 2015. Specifications Tiered GlobalSoilMap products. Release 2.4.

Guo, M., 2021: Soil Health Assessment and Management: Recent Development in Science and Practices. Soil Systems. 5, 61. https://doi.org/10.3390/soilsystems5040061

Hall M., and Voulvoulis N. 2008: Turning sustainability from an art to a science. Developing Sustainably: Drivers, techniques and case studies. SOAS, London, The Chartered Institution of Water and Environmental Management (CIWEM).

Harris, J. A., Evans, D. L., and Mooney, S. J. 2022: A new theory for soil health. European Journal of Soil Science, 73(4), e13292.

Harris, M., Hoskins, H., Robinson, A., Hutchison, J., Withers, A., Deeks, L., Harris, Way, J., and Rickson, L. 2023: JNCC Report 737: Towards Indicators of Soil Health (Project Report). https://jncc.gov.uk/

Haygarth, P.M., and Ritz, K., 2009: The future of soils and land use in the UK: soil systems for the provision of land-based ecosystem services. Land Use Policy 26, S187–S197.

Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R., and Bilgili, A.V., 2008: Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant and Soil 307, 243–253.

ISRIC, 2024: ISRIC World Soil Information. Accessed from: https://www.isric.org/ [Last accessed 26th February 2024].

Jenny, H. 1942: Actors of Soil Formation: A System of Quantitative Pedology. Dover Publications, Inc. New York.

Jian, J., Du, X., and Stewart, R. D. 2020: A database for global soil health assessment. Scientific Data, 7(16), 1-8. https://doi.org/10.1038/s41597-020-0356-3.

Kibblewhite M.G, Ritz, K, Swift, M.J. 2008: Soil health in agricultural systems. Philosophical Transactions of The Royal Society of London, B, Feb 27;363(1492):685-701. doi: 10.1098/rstb.2007.2178. PMID: 17785275; PMCID: PMC2610104.

Kirk, G.J., Bellamy, P.H. and Lark, R.M., 2010. Changes in soil pH across England and Wales in response to decreased acid deposition. Global Change Biology, 16(11), pp.3111-3119.

Kosmas, C., Kairis, O., Karavitis, C., Ritsema, C., Salvati, L., Acikalin, S., Alcala, M., Alfama, P., Atlhopheng, J., Barrera, J., Belgacem, A., Sole-Benet, A., Brito, J., Chaker, M., Chanda, R., Coelho, C., Darkoh, M., Diamantis, I., Ermolaeva, O., Fassouli, V., Fei, W., Feng, J., Fernandez, F., Ferreira, A., Gokceoglu, C., Gonzalez, D., Gungor, H., Hessel, R., Juying, J., Khatteli, H., Khitrov, N., Kounalaki, A., Laouina, A., Lollino, P., Lopes, M., Magole, L., Medina, L., Mendoza, M., Morais, P., Mulale, K., Ocakoglu, F.,Ouessar, M., Ovalle, C., Perez, C., Perkins, J., Pliakas, F., Polemio, M., Pozo, A., Prat, C., Qinke, Y., Ramos, A., Ramos, J., Riquelme, J., Romanenkov, V., Rui, L., Santaloia, F., Sebego, R., Sghaier, M., Silva, N., Sizemskaya, M., Soares, J., Sonmez, H., Taamallah, H., Tezcan, L., Torri, D., Ungaro, F., Valente, S., de Vente, J., Zagal, E., Zeiliguer, A., Zhonging, W., Ziogas, A., 2014: Evaluation and selection of indicators for land degradation and desertification monitoring: methodological approach. Environmental Management 54, pp.951–970.

Lehmann, J., Bossio, D.A., Kogel-Knabner, I., Rillig, M.C., 2020: The concept and future prospects of soil health. Nature Reviews Earth & Environment. https://doi.org/10.1038/s43017-020-0080-8 .

Loveland, P.J., Thompson, T.R.E. 2002: Identification and Development of a Set of National Indicators for Soil Quality. R&D Project P5-053, Report P5-053/02/PR. Environment Agency, Bristol, UK. Available from the Environment Agency R&D Dissemination Centre, C/o WRc, Frankland Road, Swindon, Wilts, SN5 8YF. ISBN 1 85705 667 1.

LUCAS, 2024: LUCAS: Land Use and Coverage Area frame Survey from Joint Research Centre (JRC), European Soil Data Centre (ESDAC). Accessed from: https://esdac.jrc.ec.europa.eu/projects/lucas. [Last accessed 26th February 2024].

Metzger, M.J., Shkaruba, A.D., Jongman, R.H.G., and Bunce, R.G.H., Descriptions of the European Environmental Zones and Strata, Alterra Report 2281 ISSN 1566-7197.

Merrington, G., Fishwick, S., Barraclough, D., Morris, J., Preedy, N., Boucard, T., Reeve, M., Smith, P. and Fang, C., 2006: The development and use of soil quality indicators for assessing the role of soil in environmental interactions. Report to UK SIC, SC030265, Environment Agency.

Morvan, X., Saby, N.P.A., Arrouays, D., Le Bas, C., Jones, R.J.A., Verheijen, F.G.A., Bellamy, P.H., Stephens, M., Kibblewhite, M.G., 2008: Soil monitoring in Europe: a review of existing systems and requirements for harmonisation. The Science of the Total Environment 391, pp.1–12.

NRCS, 2024: A brief history of NRCS. Accessed from: https://www.nrcs.usda.gov/about/history/brief-history-nrcs#:~:text=The%20first%20soil%20conservation%20district,appropriations%20for%20soil%20conservation%20programs [Last accessed 23rd February 2023].

OECD-Organization for Economic Co-operation and Development. 1993. OECD core set of indicators for environmental performance reviews. Paris: OECD Environment Monographs No. 83.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernandez-Ugalde, O. 2018: LUCAS Soil, the largest expandable soil dataset for Europe: A review. European Journal of Soil Science, 69(1), pp.140-153.

Panagos, P., van Liedekerke, M., Borrelli, P., Köninger, J., Ballabio, C., Orgiazzi, A., Poesen, J., & Montanarella, L. 2022: European soil data Centre 2.0: Soil data and knowledge in support of the EU policies. European Journal of Soil Science, 73(6), e13315.

Panagos, P., Van Liedekerke, M., Jones, A. & Montanarella, L. 2012: European Soil Data Centre: response to European policy support and public data requirements. Land Use Policy, 29, pp.329–338.

Powlson, D. S. 2020: Soil health—Useful terminology for communication or meaningless concept? Or both? Frontiers of Agricultural Science and Engineering, 7(3), pp.246–250.

Reynolds, B., Chamberlain, P.M., Poskitt, J., Woods, C., Scott, W.A., Rowe, E.C., Robinson, D.A., Frogbrook, Z.L., Keith, A.M., Henrys, P.A. and Black, H.I.J., 2013: Countryside Survey: National “Soil Change” 1978–2007 for Topsoils in Great Britain—acidity, carbon, and total nitrogen status. Vadose Zone Journal, 12(2).

Ritz, K., Black, H.I.J., Campbell, C.D., Harris, J.A., and Wood, C., 2009: Selecting biological indicators for monitoring soils: a framework for balancing scientific and technical opinion to assist policy development, Ecological Indicators 9(6), pp. 1212-1221 (https://doi.org/10.1016/j.ecolind.2009.02.009).

SDG Reporting, 2024: The global SDG indicators. Accessed from: https://www.sdgreporting.org/topic/indicators/#:~:text=The%20IAEG%20categorized%20the%20indicators,data%20collection%20(Tier%20III) [Last accessed 22nd February 2024].

Seaton, F.M., Robinson, D.A., Monteith, D., Lebron, I., Bürkner, P., Tomlinson, S., Emmett, B.A. and Smart, S.M., 2023: Fifty years of reduction in sulphur deposition drives recovery in soil pH and plant communities. Journal of Ecology, 111(2), pp.464-478.

Shukla, M.K., Lal, R., Ebinger, M., 2006: Determining soil quality indicators by factor analysis. Soil and Tillage Research 87, pp.194–204.

SoilGrids, 2024: SoilGrids250m 2.0 - A system for digital soil mapping based on global compilation of soil profile data and environmental layers. Accessed from: https://soilgrids.org/. [Last Accessed 26th February 2024].

SSA, 2024: England is spending little on monitoring soil quality. Accessed from: https://tabledebates.org/research-library/england-spending-little-monitoring-soil-quality [Last Accessed 22nd February 2024].

Stewart, R.D., Jian, J., Gyawali, A.J., Thomason, W.E., Badgley, B.D., Reiter, M.S., and Strickland, M.S. 2018: What we talk about when we talk about soil health. Agricultural and Environmental Letters. Research Letter.

Stone, D., Ritz, K., Griffiths, B.G., Orgiazzi, A., Creamer, R.E., 2016: Selection of biological indicators appropriate for European soil monitoring. Applied Soil Ecology 97, pp.12–22.

Toma, B.E., 2018. *The Semantics and Pragmatics of Right Dislocation: Odd thing, that* (Doctoral dissertation, The Ohio State University).

Troldborg, M., Aalders, I., Towers, W., Hallett, P.D., McKenzie, B.M., Bengough, A.G., Lilly, A., Ball, B.C., Hough, R.L., 2013: Application of Bayesian Belief Networks to quantify and map areas at risk to soil threats: using soil compaction as an example. Soil and Tillage Research 132, pp.56–68.

UKRI, 2024: United Kingdom Soil Observatory (UKSO). Accessed from: https://www.ukso.org/ [Last accessed 26th February 2024].

Valani, G.P., Martíni, A.F., Silva, L.F.S., Bovi, R.C., Cooper, M., 2021: Soil quality assessments in integrated crop–livestock–forest systems: A review. Soil Use Management. 37 (1), pp.22–36. https://doi.org/10.1111/sum.12667.

Van Lynden, G.W.J., S. Mantel and A. van Oostum 2004 (Ed.): Guiding principles for the quantitative assessment of soil degradation. Food and Agriculture Organization of the United Nations (FAO) and International Soil Reference and Information Centre (ISRIC). 2004. p. 62.

Veerman, C., Pinto Correia, T., Bastioli, C., Borbala, B., Bouma, J., and Cienciala, E., Emmett, B., Frison, E.A., Grand, A., Hristov, L., Kriaucuiniene, Z., Pogrzeba, M., Soussana, J.F. ,Vela, C.O., and Wittkowski, R. 2020: Caring for soil is caring for life —ensure 75% of soils are healthy by 2030 for food, people, nature and climate, Publications Office of the European Union, Luxembourg.

Verheijen, F.G.A., Bellamy, P.H., Kibblewhite, M.G. and Gaunt, J.L. 2005: Organic carbon ranges in arable soils of England and Wales, Soil Use and Management 21, pp. 2–9 (https://doi.org/10.1111/j.1475-2743.2005.tb00099.x).

Vogel, H. J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., Wiesmeier, M., and Wollschlager, U.2020: Quantitative evaluation of soil functions: potential and stat', Frontiers in Environmental Science, 22 (https://doi.org/10.3389/fenvs.2019.00164.

WOCAT, 2024: Welcome to WOCAT – the World Overview of Conservation Approaches and Technologies. Accessed from: https://www.wocat.net/en/. [Last accessed 23rd February 2024].