AI4SoilHealth

Indicators for soil degradation and method testing for AI4SoilHealth

D3.3.

Version 1.1
18th December 2024
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Action Number: 101086179

Action Acronym: AI4SoilHealth
Action title: Accelerating collection and use of soil health information using AI technology to support the Soil Deal for Europe and the EU Soil Observatory

HISTORY OF CHANGES		
Version	**Publication date**	**Changes**
1.0	28/11/2024	• Initial version
1.1	18/12/2024	• Updated after internal and external review

Contents

1. Introduction

The deliverable D3.3, titled "*AI4SoilHealth Indicators for soil degradation and method testing for AI4SoilHealth*," is a comprehensive effort aimed at identifying new or proxy indicators which will address soil degradation. This initiative is crucial for aligning with the EU Mission objectives and addressing gaps in standard indicators, as well as incorporating feedback from policymakers and other stakeholder groups. Conducted in collaboration with ongoing and previously produced outputs from WP2, this deliverable is crucial for meeting the eight targets set by the European Union (EU) Mission Board in the Soil Mission Implementation Plan.

Building upon previous deliverables D3.1 and D3.2, D3.3 advances the efforts to support soil health and sustainable land management across Europe. The document emphasizes the importance of soil health, which is vital for agricultural productivity, environmental sustainability, and societal well-being. Soil degradation, characterized by a range of threats including erosion, compaction, pollution, and loss of soil organic matter, poses significant challenges to maintaining soil functionality and ecosystem services.

This work presented highlights the various approaches used for addressing soil degradation, including soil quality, soil health, soil protection, and natural capital and ecosystem services. It also discusses the use of indicators in soil health assessments, highlighting the complexity and diversity of soil conditions across different regions and the need for context-specific indicators.

Overall, D3.3 aims to provide a robust framework for soil health monitoring and management, ensuring that soil resources are sustainably managed to support the EU's environmental and agricultural goals.

2. What is soil degradation?

Soil threats negatively impact the physical, chemical, and biological characteristics of soil, preventing soils from functioning to their optimum level (European Environment Agency, 2023). Addressing these threats has been a persistent challenge for EU Member States for decades and has been a focal point since the introduction of the EU Soil Thematic Strategy (European Commission, 2006).

Soil degradation is a major global threat to soil health, impacting all environments and scales. This concerns the decline in soil quality and productivity, primarily due to intensified human activities. Degradation, by definition, is *'a reduction to an inferior type or stage of development'*, which is in essence, a lowering of quality (Dictionary, 1989), while soil degradation specifically refers to *'any change or disturbance to the soil perceived to be deleterious or undesirable.'* (Johnson et al., 1997). This degradation can be exhibited in multiple ways, such as erosion, compaction, pollution, desertification, and the loss of soil organic matter (Lehmann et al., 2020; European Environment Agency, 2023). The consequences of soil degradation are significant, affecting agricultural productivity, environmental sustainability, and human well-being (Arias-Navarro et al., 2024).

The importance of prioritizing soil health cannot be overstated, as soils provide a wide range of functions essential for humans, plants and animals (Haygarth and Ritz, 2009). These functions include producing food and fibre from agriculture, storing water, improving air quality, and filtering pollutants (European Environment Agency, 2023). Additionally, soils are crucial for storing organic carbon, supplying nutrients to plants, and providing habitats for organisms.

Soil degradation, along with other soil threats, presents numerous challenges for the environment and society. It possesses significant economic impacts, particularly because of reduced crop yields, increased input costs, and higher fertilizer usage, which ultimately lead to a loss of ecosystem goods and services (Arias-Navarro et al., 2024). Therefore, by prioritizing soil health, stakeholders such as farmers, policymakers, and land managers can promote sustainable practices, formulating an appropriate strategy for safeguarding our soils and enhancing resilience.

3. Frameworks for addressing soil degradation

Given the growing importance of soil functionality for plants, animals, and humans, various frameworks have been discussed to illustrate the role of soils in society. Soil scientists have historically used several framing terms, such as soil quality (Warkentin and Fletcher, 1977; Parr et al., 1992; Bünemann et al., 2018; Faber et al., 2022), soil health (Haberern, 1992; Pankhurst et al., 1997; Lehmann et al., 2020), soil protection (Blum, 2005), and natural capital and ecosystem services (Haygarth and Ritz, 2009; Robinson et al., 2014; Dominati et al., 2010). These frameworks consistently aim to provide a hierarchy of better or worse conditions. They are usually based on a value or a range of values, designed to identify *"a framework for identifying positive (better) or negative (worse) qualities in events, objects, or situations*" (Edwards-Jones et al., 2000).

Soil resources are constantly being evaluated and reassessed, with new frameworks continuously being developed and sought after. This ongoing expansion is driven by several influences: (i) the consideration of more uses or functions of soil; (ii) the growing interest of various stakeholders in soils from different perspectives (e.g. business, finance); (iii) the development of legislation and socio-economic concepts; and the (iv) changing societal priorities (Karlen, 2011).

The succeeding sub-sections divide each of these framing terms mentioned above in more detail.

3.1. Soil quality and soil health

Soil quality can be defined as "*the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal (including human) health*" (Doran and Parkin, 1996). Usually, soil quality is related to a specific purpose and is context-specific.

Initially, soil health was regarded as an alternative term for soil quality (Heberern, 1992). However, increasing discussions in the 1990s led to researchers such as Pankhurst et al. (1997) differentiating between the concepts. Their research defined soil health as encapsulating the soil's ecological attributes which have implications beyond its capacity to produce a particular crop type. These attributes range from soil biota, biodiversity, food web structure, activity, and the range of functions performed. As a result, contemporary definitions of soil health were designed including "*the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans, and connects agricultural and soil science to policy, stakeholder needs, and sustainable supply-chain management*" (Lehmann et al, 2020) and "*the continued capacity of soils to support ecosystem services*" (EU Mission on Soil Health and Food, 2023).

Notable authors such as Bünemann et al. (2018) suggest that soil health and soil quality can be used interchangeably. However, soil quality is often narrower in focus, concentrating on how well the soil meets the specific human or environmental needs for a particular purpose. Conversely, soil health is broader considering the overall sustainability of soil as a living ecosystem. Notably, quality focuses on functionality, while health concentrates on vitality and resilience. Furthermore, quality is often discussed in the short-term, focusing on performance over a few years (1-5 years), whereas health considers longer time frames with a particular note towards a soil's capacity to remain productive and resilient over time.

3.2. Soil protection

Unlike soil health and soil quality, which focus on the condition and functionality of soils, soil protection is concerned with mitigating risks that can lead to soil deterioration (Blum, 2004).

The Soil Strategy (European Commission, 2006) identified eight primary threats to soil across the European Union (**Table 1**), highlighting the wide-ranging challenges and difficulties that soil protection efforts must address:

Table 1: Soil Threats and their associated challenges and difficulties

Soil Threat	**Challenges and Difficulties**
Erosion	Removal of the topsoil layer by wind, water, or human activity, which reduces soil fertility and can lead to loss of arable land.
Decline in Organic Matter	Reduction of organic material in the soil, which is crucial for maintaining soil structure, fertility, and biological activity.
Soil Contamination	Local or widespread industrial activities, agricultural practices, and urban development, leading to the accumulation of harmful substances in the soil.
Soil Sealing	The covering of soil with materials such as concrete and asphalt, preventing natural soil functions such as water infiltration and gas exchange.
Soil Compaction	Compression of soil particles, because of heavy machinery or livestock, leading to a reduction in pore space, impeding root growth and water movement.
Decline in Soil Biodiversity	Loss of soil organisms which play essential roles in nutrient cycling, organic matter decomposition, and soil structure maintenance.
Soil Salinisation	Accumulation of soluble salts in the soil which can inhibit plant growth and reduce soil fertility.
Flood, Inundation and Landslides	Destabilization of soil due to excess water, leading to erosion, loss of soil structure, and increased risk of landslides.

To combat these threats, various strategies and practices are implemented. Such strategies range from erosion control, land use planning, pollution prevention, biodiversity enhancement and flood and landslide prevention.

Soil protection is a multifaceted approach which requires addressing many threats to maintain soil health and functionality. By implementing effective management practices and policies, it is possible to mitigate soil degradation, ensuring the sustainability of soil resources for future generations.

3.3. Natural capital and ecosystem services

Natural capital (Robinson et al., 2017) and ecosystem services (Dominati et al., 2010) are concepts which originated in ecology (Gómez-Baggethun et al., 2010). Concurrently, soil science concentrated on perceptions of health and threats. In soil science, natural capital generally pertains to the soil's stocks and structure (Robinson et al., 2017) whilst, conversely, ecosystem services highlight the benefits that humans receive from nature's goods and services, particularly from an anthropocentric perspective. A crucial dimension of the ecosystem service framework is to emphasise the value of nature. This can often be a translation of value into monetary terms, leading to green accounting frameworks (SEEA, 2024). These acknowledge the value of nature by providing satellite accounts which complement indices such as Gross Domestic Product (GDP).

3.4. Other frameworks

Many other frameworks exist to varying degrees of development and use, ranging from soil tilth (Karlen, 2011); soil fertility (Blum, 2005; Frossard et al., 2006); land capability (Bibby et al., 1991; USDA Natural Resources Conservation Service, 2024), and overarching themes such as soil security (McBratney et al., 2014, Basset, 2024). Common to all these frameworks is the use of indicators to assess the status and change of the soil resource.

4. Use of indicators in soil health assessments

Indicators are often required to assess the state or condition of the soil and are interpreted in connection to whichever framework is used. Often the same indicators are used for different frameworks, but their interpretation, especially the thresholds, is likely to be different depending on context. Moreover, no single indicator fully captures a soil's characteristics or attributes meaning that a selection of indicators is generally required (Nortcliff, 2002). In this context, an indicator can be defined as "*a metric derived from parameters that describe the state of the environment, assessing its impact on human beings, ecosystems, and materials*" (OECD-Organization for Economic Co-operation and Development. 1993; Faber et al, 2022) with indicators often categorized based on the physical, chemical and biological characteristics of soil (Bünemann et al., 2018).

Previous studies have highlighted the complexity and diversity of selected soil indicators for analysis and evaluation (Bünemann et al., 2018; Ritz et al., 2009; Merrington et al., 2006, Loveland and Thompson, 2002, Corstanje et al., 2017). Moreover, these examples confirm the requirement for environmental-specific indicators which can accurately reflect soil conditions and help inform policy development, management practices or desired interventions. This is crucial for providing improved and informed guidance on policy and ensuring sustainable environmental practices (Bünemann et al., 2018). However, selecting appropriate soil indicators, especially at pan-European scale, presents significant challenges due to varying climate conditions, pedological environments, geology and multifunctional uses which result in soil processes being displayed. This will lead to an increasing variability in behaviour and optimums across different pedo-climatic zones. Hence, the development of an appropriate set of principles for selecting soil indicators is appropriate. These must provide clear criteria for indicator selection and ultimately, must inform a range of different stakeholders (e.g. farmers, land managers and policy makers) depending on their purposes.

Recently, the policy landscape surrounding soils has gained increased traction across Europe, with a particular drive being increased since the evolving European Union Green Deal (Montanarella and Panagos, 2021) and the recent development of the European Union's Soil Monitoring Law (European Commission, 2023a). Within the law, twelve soil descriptors are proposed for soil health assessment. These descriptors include both indicators, which measure specific functions, and interpretive metrics, which provide context and enhance the interpretation of these indicators. For example, soil organic carbon (SOC) is an indicator of carbon used for climate regulation, whereas texture is an interpretive metric that when combined in the form of the SOC: clay ratio can provide added insight into the interpretation (Feeney et al., 2024).

5. The paradigm of quality

Quality is a concept which is often sought after but challenging to define. It is an aspiration discussed across various fields, including education (Cheng and Tam, 1997), health (Busse et al., 2019), business (Forker et al., 1996), manufacturing (Gunasekaran et al., 1994), and the environment (Johnson et al., 1997). The importance of quality lies in its influence on how it is used in decision-making and subsequent actions, which are often based on how quality is framed initially.

In the context of soil science, the terms 'quality' and 'health' are sometimes used interchangeably, but they have distinct meanings as mentioned previously. For the context of soils, quality typically refers to the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health. It is often context-specific and related to a particular purpose. On the other hand, the health of soils concentrates on the broader attributes of soil, including its vitality and resilience to sustain plants, animals, and humans.

Moving forward, D3.3 will use the concept of quality to frame the discussion on soil degradation and the selection of appropriate indicators for soil health assessment. Noting these distinctions will increase the development of indicators and interpretive metrics, ensuring that they are relevant and effective for monitoring and managing soil health across different contexts and scales.

According to Harvey and Green (1993), the concept of quality can be compared in two different ways: it is dependent on the evaluator and their perspective. The assessment of quality varies depending on who is making the judgment. As the authors note, "*this is not a different perspective on the same thing but different perspectives on different things with the same label*." Additionally, conceptions of quality can differ based upon perspectives, ranging from absolute or intrinsic quality to meeting a standard or achieving consistency. Thus, "*some conceptualisations of quality are rather more 'absolutist' than others*" (Harvey and Green, 1993).

In short, quality is inherently subjective, involving comparisons of what is considered 'better' or 'worse'. This subjectivity is crucial in the context of soils, as it underpins the framing of quality, its operationalization, and the selection of indicators.

Quality can have different meanings depending on the context, which can often lead to misunderstandings. It can refer to excellence (the degree of distinction or superiority), a standard (how good or bad something is), or a characteristic (a feature of something) (Cambridge Dictionary Online, 2024). Additionally, Harvey and Green (1993) compartmentalise the concept of quality into five categories: 1) exception, 2) perfection, 3) fitness for purpose, 4) value for money, and 5) transformative. Examples are provided below, using examples outside of soils as a basis to work towards.

- **Exception 1a. Without a Standard**: This concept is often used in branding. For example, Champagne is considered higher quality than other sparkling wines simply because it comes from the Champagne region of France.
- **Exception 1b. With a Standard**: Here, a high-quality product exceeds a specific high standard. For instance, ultra-pure water is considered higher quality than tap water in a laboratory setting.
- **Perfection 2a. Zero Defects:** While achieving zero defects is desirable, it is often not feasible in practice. Therefore, an acceptable threshold is set. In water quality, a 'true zero defects' example might be zero E. coli per 100ml of water, whereas an acceptable threshold could be less than 50mg of nitrate per litre of water.

- **Perfection 2b. Consistency:** This aspect of perfection focuses on developing a quality culture at every stage of a process to ensure things are done right the first time. For example, maintaining all processes to ensure tap water is safe for consumption when it comes out of the tap.
- **Fitness for Purpose 3. Function or Use:** Quality is defined by how well something serves its intended purpose. For example, an athlete might consider isotonic water to be of higher quality than non-isotonic water for rehydration.
- **Specification and Cost 4.:** This relates to the balance between the level of specification and the cost. For example, comparing the value of bottled water versus tap water.
- **Fundamental Change 5:** This type of quality is characterized by a fundamental change in nature, such as ice turning into liquid water.

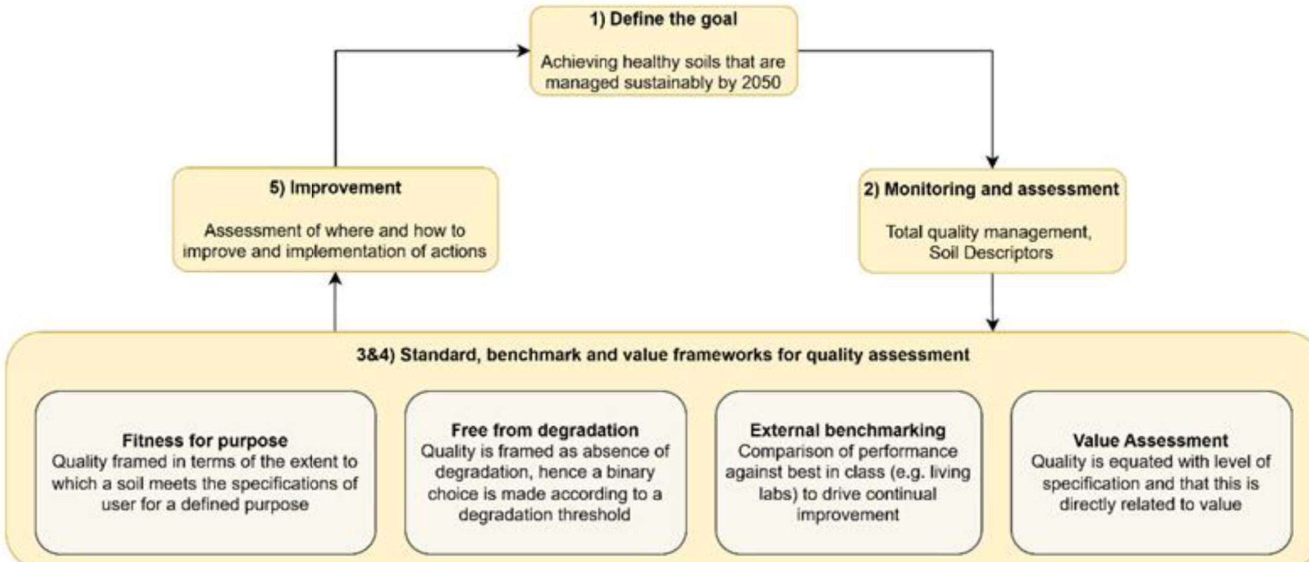
5.1. Total quality management

During the mid-20th century, many businesses primarily adopted a reductionist approach to improve quality; once a standard was reached, users or stakeholders went no further with improvement efforts. However, a significant philosophical shift occurred with the introduction of systems thinking. This method concentrates on the entire system rather than focusing on it as individual components, aiming to understand the interactions amongst all components within a system. In the realm of science, this concept is represented by general systems theory.

When adopting a quality approach, it is crucial to recognize the paradigm shift in quality assessment, which is based upon the principles of systems thinking and the integration of Total Quality Management (TQM) (Beckford, 2010). TQM aims for continual quality improvement and may adopt any of the quality approaches to achieve the relevant goals and objectives. The quality frameworks described earlier can all be placed within this context. However, each approach can potentially suffer from a reductionist viewpoint, where quality is pursued by focusing on a single aspect of a system rather than focusing on the system as a whole.

Thus, within the context of the Mission Soil initiative, all the quality approaches discussed should be considered using a TQM mindset. Several of the quality approaches are illustrated in **Fig. 1**, where (i) the quality goal is defined (e.g., for the EU Mission, achieving sustainably managed healthy soils by 2050), (ii) the appropriate monitoring framework and indicators for the respective quality approach are selected, and (iii) the implementation of actions, typically interventions, is improved. The TQM framework aligns with the

Drivers, Pressures, State, Impact, and Response (DPSIR) structure. These frameworks presented in **Fig. 1** provide practical solutions to real-world problems, often from the perspectives of different stakeholders.



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

Fig. 1. The Total Quality Management (TQM) framework for continuous improvement and various quality approaches in soil science.

The Mission Soil initiative aims to achieve TQM through living labs, co-creation, and co-design to address and overcome barriers (European Commission, 2023b). Therefore, when evaluating quality, several aspects must be considered: (i) defining the desired outcomes, (ii) improving communication methods, (iii) identifying key communication targets, (iv) determining the motivations needed to drive change, (v) measuring and monitoring the system, and (vi) identifying and overcoming barriers and constraints. Tackling these challenges is critical for making significant impacts and providing insights which align with the practical goals of Mission Soil. Ultimately, sustainability is not just about repairing damage but preventing it from reoccurring in the future. This can be achieved through a fundamental change in mindset and practice. Thus, by adopting a philosophical shift amongst stakeholders, soil management supply chains, and consumers towards continual improvement, this should leave a more lasting legacy for Mission Soil than merely addressing a specific level of degradation.

5.1.1. Assessment frameworks in the context of soils

Within the TQM framework (**Fig 1.**), four quality framings are identified with key characteristics below each row. These are "*Fitness for Purpose*; "*Free from Degradation*"; "*External Benchmarking*", and "*Value Assessment*".

Each framing addresses a particular problem, and these are explored in the following sections.

5.1.2. Soil quality in the context of "*fitness for purpose*"

Conceptually, "*fitness for purpose*" means that the definition of quality is connected to an intended purpose. This requires clearly defining the purpose and identifying "*who*" this serves. Additionally, the criteria for determining fitness must be established and demonstrated. In the soil literature, quality frameworks initially focused on food production, with the purpose specified from the grower's perspective. The fitness component was assessed based on the suitability for crop production in agriculture, formulating the basis of the Cornell Comprehensive Assessment of Soil Health (CASH) framework (Norris et al., 2020). Indicators are interpreted based on their suitability for crop production, with fitness determined by assigning values ranging from 0 to 100 using three groups: "*More is better*," "*Optimum curve*," and "*Less is better*" (Svoray et al., 2015).

Regarding the "who," Harvey and Green (1993) divided fitness for purpose into two perspectives: the customer's and the institution's mission. For soils, "*customer*" can be translated to a user (e.g., grower or forester), while "*mission*" can be better understood as society and public goods, recognizing soil's role in providing multiple ecological and societal benefits. Research is ongoing to develop broader frameworks based on fitness for purpose which consider various land uses and the delivery of ecosystem goods and services (e.g., food production) (Harris et al., 2023)).

5.1.3. Zero defects soil quality assessment as *"free from degradation"*

The "*zero defects*" approach recognizes that soil health can be compromised by degradation threats such as the loss of soil organic matter (SOM), pollution, compaction, and erosion (Blum, 2004). Unlike an "*exception*" framing of quality, zero defects are defined by meeting specifications and meeting the minimum required standards or criteria, rather than exceeding high standards. For example, in the context of EU soils, quality is defined as "*the absence of significant anthropogenic degradation*." The Soil Protection Framework is well established, and threats are widely recognized with broad consensus (Stolte et al., 2016). Soil threats (e.g., degradation and erosion) are conditions which damage or reduce a soil's capacity to provide ecosystem goods and services (Baritz et al., 2021). These threats negatively affect a soil's physical, chemical, and biological characteristics, preventing it from performing to its optimum capacity. Addressing soil threats has been a continuous challenge for all EU Member States for many decades and has been regularly discussed since the introduction of the EU Soil Thematic Strategy (European Commission, 2006). Therefore, it is not surprising that the Soil Monitoring Law at the EU level does not adopt a fitness for purpose approach but instead uses a "*free from degradation*" quality perspective.

Currently, the EUSO assesses quality as a binary choice: either it is degraded or not based on a threshold for a soil threat. Soils that remain within acceptable degradation levels are considered to be satisfactory in quality and do not require restorative intervention (Feeney et al., 2023). However, this framework does not define an optimum level and therefore is limited in this regard. In this case, a healthy soil is simply considered one that is not degraded beyond an acceptable level. The threat-based approach aligns with the operational concepts of the EU based on the DPSIR framework (OECD-Organization for Economic Co-operation and Development, 1993). Drivers and pressures impact the state or condition of the soil, leading policy to assess impacts and responses through interventions to prevent degradation and restore soils.

5.1.4. *"External benchmarking"*

Benchmarking involves obtaining the sample distribution of a population based on well-defined characteristics (e.g., loam soils under arable cultivation). There are different ways to approach benchmarking. A sampled population of a soil metric can be used to either (i) determine a mean or median as a standard for comparison, or (ii) examine the upper and lower quartiles or percentiles to identify top or poor-performing soil managers.

The first approach develops benchmark values taken from representative datasets, allowing for comparison with regionally representative measured distributions. However, this method does not directly evaluate specific soil functions (Bünemann et al., 2018; Verheijen et al., 2005). For example, if the pH of an arable soil typically clusters around a value of pH 5, this would be selected as an optimal benchmark value. This approach has been criticized because the soils used to establish these benchmarks may already be highly degraded. Therefore, benchmarks based on regional values of degraded soils are not particularly useful.

In contrast, external benchmarking, which is more commonly adopted by practitioners, provides a different framing for consistency. This approach is useful for soil managers who compare their soil performance indicators (e.g., soil organic carbon (SOC)) against the performance of the same indicators collected by other soil managers for similar soils and land use (**Fig. 2**.). This method allows for a more practical and relevant comparison, helping managers identify best practices and areas for improvement.

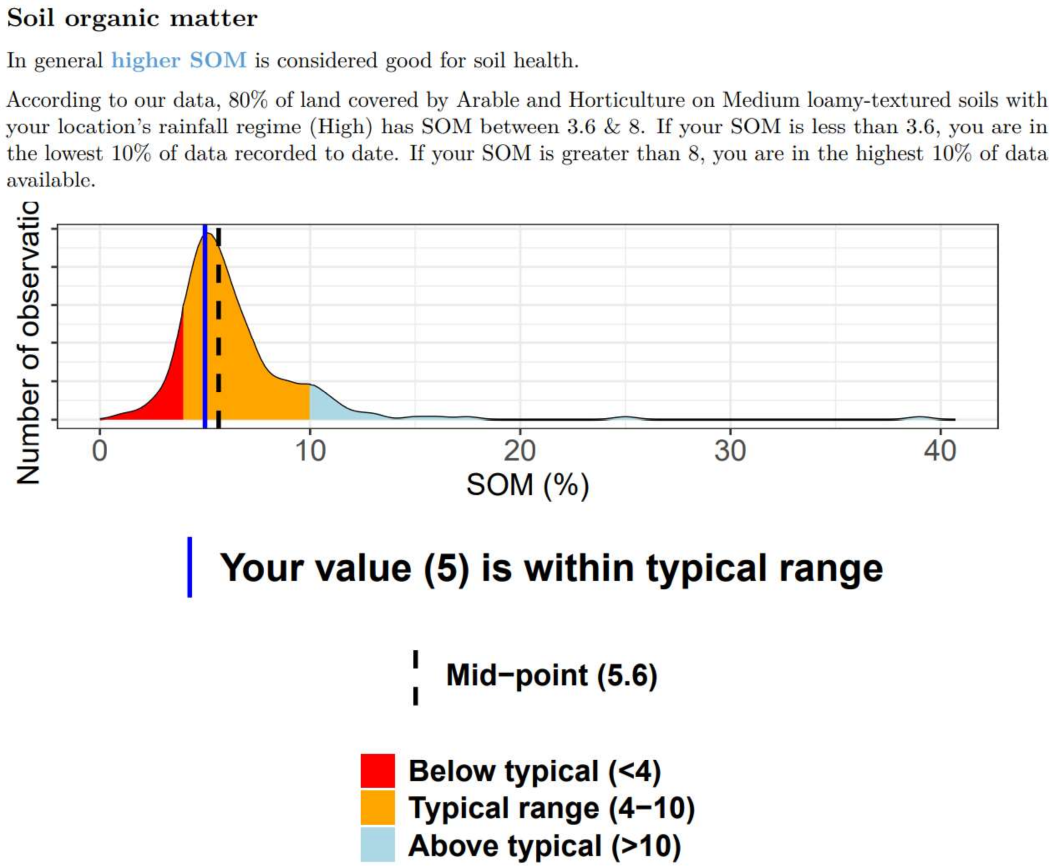


Fig. 2. An example of the output from The SOil funDamentals (SOD) tool (SOD, 2024) described in Feeney et al., (2023). The distribution presented is for a medium loam soil under cropland management generated from Countryside Survey monitoring data (Robinson et al., 2024). The blue line represents stakeholder input so they can compare where they sit in comparison to all soils of this texture in this management class.

In this context, benchmarking identifies and interprets the best-performing quantile or given percentile of a distribution, using it as an indicator of top performance. This process is always related to a specific region within a defined time frame. By analysing the management practices or characteristics in the best quantile, bench-markers aim to understand how and why top performance is achieved, which is crucial for guiding improvements. For example, SOC levels are measured across farms with the same soil types. Farmers can see the distribution of SOC levels across these farms and compare this with their own farm's performance. If they fall in the bottom half of the distribution, they can visit the farms in the top half to learn what management practices they could adopt to improve their SOC levels. This creates a continuous cycle of investigation and learning to ensure best practices are identified, adopted, and implemented (Juran and Godfrey, 1999).

Combining thresholds and benchmarks offers a robust approach to soil health assessment. Feeney et al. (2023) used multiple soil indicators—such as soil organic matter, bulk density, pH, and earthworm counts—to evaluate soil health across Great Britain. Similarly, Gutierrez et al. (2024) applied this approach in Denmark, using indicators like organic carbon content, bulk density, pH, electrical conductivity, clay-to-carbon ratio, water erosion, and nitrogen leaching. Outcomes from these studies provided a comprehensive understanding of soil health, identified effective soil management practices, and highlighted areas which require improvement. Additionally, Gutierrez et al. (2024) informed policymakers about the current state of soil health and the effectiveness of existing practices, aiding in the development of more targeted and effective soil health policies.

Both of these studies offered several benefits, including providing a holistic view of soil health by capturing various aspects of soil functionality and degradation. By adopting the benchmarking approach, successful soil management practices were identified that could be replicated in other areas. However, there are also potential negative impacts or challenges associated with using these benchmarking approaches. The variability in soil conditions across different regions can make it challenging to establish universal benchmarks. Similar indicators and proxies can be included in the benchmarking concept, but the feasibility will vary. As a result, this can lead to discrepancies in soil health assessments and management recommendations. Moreover, collecting and analysing soil data for multiple indicators can be resource-intensive and time consuming. The studies used by Feeney et al. (2023) and Gutierrez et al. (2024) were based on comprehensive national soil databases, which may not be uniformly available across all EU countries. Establishing similar databases EU-wide would require significant investment in soil monitoring infrastructure and data collection efforts. Finally, relying on quantitative indicators may overlook qualitative aspects of soil health, such as local knowledge of stakeholders such as farmers, and context-specific measures that are crucial for effective soil management. National legislation and policy will also play a significant role. Some countries may have stronger soil health regulations and monitoring systems, which could influence the implementation of benchmarking practices.

Overall, while the concept of combining thresholds and benchmarks is promising for soil health assessment, its application across the EU will require careful consideration of data availability, regional variability, and the integration of both quantitative and qualitative indicators. Addressing these challenges will be essential for ensuring comprehensive and sustainable soil health assessments across the EU.

5.1.5. *“Value assessment”*

According to Obst, (2016), *value assessment* is a relatively new discussion conversation for soils. Frameworks such as natural capital and green accounting include soils but require much development (SEEA, 2024; Dominati et al., 2014). In this scenario, the goal of natural capital and ecosystem services is to acknowledge the economic value of soil resources. Green accounting aims to highlight the value of natural capital stocks, and the ecosystem services provided by nature, enabling decision makers to compare natural solutions with engineered alternatives. Hence, maintaining natural capital is seen as fundamental to human economic activity and well-being across the EU. Thus, “*The need to conserve and enhance natural capital*” is seen as an explicit policy target in the EU's Biodiversity Strategy for 2020 and its 7th Environment Action Programme (European Environment Agency. 2019).

The Cost-Reflective Conservation Framework (CRCF) can be integrated into this discussion as it emphasizes the importance of reflecting the true costs of conservation efforts in an economic context. By incorporating CRCF, decision-makers can gain a better understanding of the financial implications of soil conservation and management practices. As a result, more informed and sustainable choices can be reached with clarity.

From what we have presented, different approaches to framing soils in a quality context exist. However, there is no “*right*” or “*wrong*” perspective to take; different frameworks will be harder or easier to operationalise outcomes.

6. Indicator selection in the context of the EU Mission Soil

The launch of the EU Green Deal in 2019 highlighted the crucial role of healthy soils in EU policies. Healthy soils are vital for achieving several EU Green Deal targets, including sustainable farming and forestry, biodiversity, zero pollution, sustainable food provision, a resilient environment, and climate neutrality (Panagos et al., 2022). Additionally, the publication of the EU Soil Strategy for 2030 and the proposed Soil Monitoring Law (SML) marked significant milestones for soil protection and restoration in EU politics. The EU Mission “*A Soil Deal for Europe*” further supports the EU's ambitions for soil health and sustainable land management. The Mission Soil aims to establish 100 Living Labs and Lighthouses to co-create, test, and pioneer innovations for soil health, while also advancing knowledge on healthy soils. Given these ambitions, a systematic and harmonized soil monitoring framework at the EU scale is required, along with a robust set of measurable indicators that reflect the state of soil health across the EU. This is critical to determine where and to what extent relevant actions are required and to evaluate the effectiveness of such actions.

To evaluate soils at the pan-European level and inform policymakers on interventions, a "*fitness for purpose*" approach is less suitable at this scale. Instead, the soil protection and threats "*free from degradation*" outline is more appropriate and useful for informing policy.

In this context, the EU Soil Observatory (EUSO), hosted within the Joint Research Centre of the European Commission, recently launched its EUSO Soil Degradation Dashboard (EUSO, 2024; Panagos et al., 2024a). The EUSO Dashboard aims to capture and monitor the state of soils within the EU based on a set of soil degradation indicators at the EU level. Indicators are selected based on their relevance and data availability for pan-EU assessment. Currently, the EUSO Dashboard includes 19 indicators (**Table 2**), aligning with the main soil degradation processes and indicators discussed in the scientific literature (e.g., Bünemann et al., 2018; Stolte et al., 2015). EU-wide thresholds have been defined for each indicator to determine whether soils are degraded or non-degraded. These thresholds estimate the point beyond which soils are significantly affected by a specific degradation process.

If any indicator reaches the threshold, the soil is classified as "*degraded*." This "*one out, all out*" principle aligns with the free-from-degradation approach presented in **Fig. 1**. Thus, the EUSO Soil Degradation Dashboard provides a spatial assessment of soil health at the EU level using a free-from-degradation approach. Although the dashboard comes with uncertainties (Panagos et al., 2024a), it is a powerful new application to inform policymakers about where interventions are required to support healthy soils. In the coming years, the EUSO Soil Degradation Dashboard will be regularly updated to complete the assessment of soil degradation processes in Europe. New indicators for missing soil degradation processes (e.g., diffuse pollution, salinization, biodiversity) have been updated, and existing indicators will continue to be developed with new available data (Prăvălie et al., 2024). Additionally, thresholds will be refined and recalibrated to account for differences in pedo-climatic conditions. These further updates and improvements to the EUSO Dashboard will require close collaboration with Mission Soil-funded projects (see also Panagos et al., 2024b).

Table 2. Soil degradation indicators included in the EUSO Soil Degradation Dashboard, and their respective thresholds and data sources.

Soil degradation processes	Indicator	Threshold	Reference
Soil erosion	Water erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Panagos et al., 2020
	Wind erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Borrelli et al., 2017
	Tillage erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Borrelli et al., 2023
	Harvest erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Panagos et al., 2019
	Post fire recovery	Recovery rate < 1	Vieira et al., 2023
Loss of organic soils	Peatland degradation risk	Peatlands under hotspots of cropland	UNEP, 2022
Loss of soil organic carbon	Distance to max SOC level	Distance to max SOC level > 60%	De Rosa et al., 2024
Soil pollution	Copper excess	Cu concentration > 100 mg kg^{-1}	Ballabio et al., 2018
	Mercury excess	Hg concentration > 0.5 mg kg^{-1}	Ballabio et al., 2021
	Zinc excess	Zn concentration > 100 mg kg^{-1}	Van Eynde et al., 2023
	Cadmium excess	Cd concentration > 1 mg kg^{-1}	Ballabio et al., 2024
	Arsenic excess	P (X > 45 mg kg^{-1}) > 5%	Fendrich et al., 2024
Soil sealing	Built-up areas	No threshold (all built-up areas)	Copernicus, 2018
Soil compaction	Packing density	Packing density ≥ 1.75 g cm^{-3}	Panagos et al., 2024b

Soil nutrients	Nitrogen surplus	Agricultural areas where N surplus > 50 kg $ha^{-1} yr^{-1}$	Grizzetti et al., 2023;
	Phosphorus deficiency	P deficiency < 20 mg kg^{-1}	Ballabio et al., 2019
	Phosphorus excess	P excess > 50 mg kg^{-1}	Ballabio et al., 2019
Loss of soil bio-diversity	Potential threat to biological functions	≥ Moderately-High level of risk	Orgiazzi et al., 2016
Salinization	Secondary salinization risk	Areas in the Mediterranean region where >30% is equipped for irrigation	Siebert et al., 2013

A similar "*free from degradation*" approach is proposed in the SML. In the SML, soil health is evaluated based on the measurement or model-based determination of 12 soil descriptors, describing physical, chemical, and biological soil characteristics. These descriptors should match a certain criteria or threshold, set at the EU or Member State level. In essence, if one of the descriptors does not meet the criteria set, the respective soil is classified as unhealthy. Intact soil health is therefore framed as any unacceptable level of degradation processes being absent.

7. Developing a vulnerability index based on degradation

Lehmann et al. (2020) highlight the challenges in creating a soil-health index due to the requirement for quantitative transformation and weighting of multiple indicators. The traditional definition of soil quality as the "*capacity to function*" implies a fitness for use framework, which requires both function assessment and performance criteria. This has led to the exploration of alternative quality assessment frameworks, such as benchmarking and modified quality control approaches based on degradation frequency.

Effective assessment methodologies are critical for understanding soil degradation and informing targeted interventions. Various studies have used different approaches, including counting specific soil threats (Gianoli et al., 2023; Panagos et al., 2024a; Prăvălie et al.,2024), assessing trends in soil degradation indicators aligned with sustainable development goals (Cherif et al., 2023; Yang et al., 2023), and employing fuzzy logic-based techniques (Lu et al., 2022). However, these methods often rely on subjective thresholds, which lead to binary assessments that are unlikely to capture the full complexity of soil degradation.

Recently, the introduction of a soil vulnerability index (SVI) has been proposed to transform binary categorizations into a continuous metric, offering a more objective way to quantify soil vulnerability to degradation (Afshar et al., in review). The SVI combines key indicators such as soil erosion rate, electrical conductivity (EC), soil organic carbon (SOC), and pH. Evaluation of the SVI across Europe revealed significant spatial and temporal variability in soil vulnerability. Higher SVI values (representing higher vulnerability and unhealthier conditions) were observed in southern regions like Spain, while northern and central Europe exhibited lower values.

The analysis of using an AI model to link the SVI with various environmental and soil degradation drivers, highlighted the roles of management practices, air temperature, and soil nutrients on the variability of SVI across Europe (Afshar et al., in review). The development of the SVI and its implementation with AI represents a significant improvement in global soil degradation assessments, leveraging climate and remotely sensed data to inform sustainable land use practices. As soil degradation intensifies with climate change and land use pressures, tools like the SVI and AI models can guide soil conservation strategies and maintain soil health worldwide.

Application of SVI in soil health assessment, reveals the need for careful interpretation of results as a guide for further investigation rather than a definitive assessment. The framework can be expanded with additional indicators and agreed responses to degradation.

Summary

In deliverable D3.3, we have examined and created a recommended selection framework for assessing the appropriate Soil Health Indicators (SHIs) for soil degradation. This deliverable provides important guidance and recommendations for facilitating subsequent work in WP4, 5, and 6. The report acknowledges that selecting the most appropriate indicators must consider the detection of state and change, ensuring that the indicators provide a range of desired soil ecosystem functions and services to plants, animals, and humans.

The report aligns with the EU Mission Board's objectives and targets set in the Soil Mission Implementation Plan, aiming to develop a list of appropriate SHIs that can be used across multiple channels. The Soil Monitoring Law (SML) and future policy and management objectives should help facilitate this. Based on the information contained in D3.3, this should set the stage for other deliverables in WP3.

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