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

Grant A. Campbell[1] | Pete Smith[1] | Nils Broothaerts[2] | Panos Panagos[2] | Arwyn Jones[2] | Cristiano Ballabio[2] | Daniele De Rosa[3] | Lis Wollesen de Jonge[4] | Emmanuel Arthur[4] | Lucas Gomes[4] | Nima Shokri[5,6] | Mehdi Afshar[5,6] | Gergely Tóth[7] | Peter Lehmann[8] | Pasquale Borrelli[9,10] | Christine Alewell[10] | Robert Minarik[11] | Tomislav Hengl[11] | Ichsani Wheeler[11] | Lindsay Maskell[12] | Madlene Nussbaum[13] | Laurence Jones[14] | Christopher J. Feeney[14] | David A. Robinson[14]

[1]Institute of Biological & Environmental Sciences, University of Aberdeen, Aberdeen, UK | [2]European Commission, Joint Research Centre (JRC), Ispra, Italy | [3]Department of Agriculture, Forestry, Food and Environmental Sciences, University of Basilicata, Potenza, Italy | [4]Department of Agroecology, Aarhus University, Tjele, Denmark | [5]Institute of Geo-Hydroinformatics, Hamburg University of Technology, Hamburg, Germany | [6]United Nations University Hub on Engineering to Face Climate Change at the Hamburg University of Technology, United Nations University Institute for Water, Environment and Health (UNU-INWEH), Hamburg, Germany | [7]HUN-REN Agricultural Research Centre, Institute for Soil Sciences, Budapest, Hungary | [8]Soil and Terrestrial Environmental Physics, ETH Zurich, Zurich, Switzerland | [9]Department of Science, Roma Tre University, Rome, Italy | [10]Department of Environmental Sciences, Environmental Geosciences, University of Basel, Basel, Switzerland | [11]OpenGeoHub, Doorwerth, the Netherlands | [12]UK Centre for Ecology & Hydrology, Lancaster, UK | [13]Department of Physical Geography, University of Utrecht, Utrecht, the Netherlands | [14]UK Centre for Ecology & Hydrology, Bangor, UK

Correspondence: Grant A. Campbell (grant.campbell@abdn.ac.uk)

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ABSTRACT

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

Degradation', 'External Benchmarking' and 'Value Assessment', with each possessing a unique role and application. Notably, the 'Free from Degradation' framework is emphasised for its alignment with soil protection efforts and its relevance to soil threats. This makes it particularly suitable for pan-European assessments conducted by the European Union Soil Observatory (EUSO).

1 | Introduction

Soils play a crucial role in providing a mixture of ecological and non-ecological functions (Blum 2005) essential for environmental sustainability and human activities. Ecological functions range from biomass production, earth system regulatory processes which protect humans and the environment and serving as a habitat for biodiversity. Conversely, non-ecological functions relate to the physical support for human infrastructure, the provision of raw materials and the preservation of cultural heritage (Blum 2005; Ritz et al. 2009; Baritz et al. 2021; European Environmental Agency 2023; Haygarth and Ritz 2009; Robinson et al. 2017; Smith et al. 2021; Shokri et al. 2024). These functions have significantly influenced the communication strategies of the European Union (EU) and the United Nations (UN) with respect to soil management.

The growing acknowledgment of the importance of soils to plants and humans has led to the development of various frameworks which articulate the relationship between soils and society. These frameworks often highlight the concept of value, which can be defined as 'a means to assess the positive or negative qualities of events, objects or situations' (Edwards-Jones et al. 2000). The chosen perspective on value can be anthropocentric—focusing on the utility of soils—or biocentric, recognising the intrinsic value of nature (Robinson et al. 2014). This distinction affects how soil quality and health are perceived. Quality is often associated with anthropocentric perspectives and health is linked to a more holistic understanding of the role of soils in ecosystems. Kibblewhite et al. (2008) aimed to distinguish between soil quality and health, suggesting quality is more aligned with a 'reductionist' approach based on specific indicators of soil properties. In contrast, health is seen as a more holistic and 'integrated' concept encompassing the complexity and emergence within soil systems. Consequently, the interpretation of the significance of soil can differ depending on the philosophical lens applied, leading to many diverse frameworks which highlight its importance, value or quality.

This paper focuses on identifying various approaches to soil assessment within quality frameworks, with the overall aim of improving the understanding of indicator selection and interpretation for specific purposes. It deploys the Driver-Pressure-State-Impact-Response (DPSIR) model, categorising indicators into leading, concurrent and lagging types, before considering these indicators based on tiers of development or suitability for soil quality assessment. This structured approach facilitates the selection of indicators for monitoring which align with relevant scientific and policy directions. Additionally, the paper examines the European Union Soil Observatory (EUSO) assessment framework in relation to quality considerations, positioning it within the context of the Directive on Soil Monitoring and Resilience (also known as the Soil Monitoring Law [SML]; European Commission 2023). The frameworks discussed in this paper aim to support ongoing initiatives to safeguard soil resources and foster sustainable environmental practices throughout Europe.

1.1 | Common Soil Assessment Frameworks

Soil resources are regularly subjected to ongoing measurement and review, influenced by the requirement to incorporate a broader range of soil functions, increased stakeholder interest, evolving legislation, changing societal priorities and the integration of soils into wider ecosystem evaluation frameworks (e.g., Natural Capital accounting) (SEEA 2024; Karlen 2011). This evolution reflects a growing recognition of the multifaceted roles soils play in environmental and economic situations.

Soil scientists adopt various framing terms to investigate soil. These range from soil quality (Taychinov 1971; Warkentin and Fletcher 1977; Parr et al. 1992; Bünemann et al. 2018; Faber et al. 2022), soil health (Haberern 1992; Pankhurst 1997; Kibblewhite et al. 2008; Lehmann et al. 2020), soil protection (Blum 2005) and concepts related to natural capital and ecosystem services (Haygarth and Ritz 2009; Robinson et al. 2014; Dominati et al. 2010; McBratney et al. 2014). These terms have been developed and refined over many decades, indicating a rich academic discussion surrounding soil science. The references to the foundational studies listed above highlight the historical context and the progressive understanding of the significance of soils across both ecological and socioeconomic frameworks.

Harris et al. (2023) advocate for a whole system approach to soil health assessment, emphasising the need for a hierarchical framework which reflects the organisation and development of soil ecosystems, in other words, 'embracing interrelated signs of life, function, complexity and emergence'. Despite the aspiration for integrated soil health assessments, the current lack of a standardised measurement framework means that there is a reliance on 'reductionist' indicators. However, measurements such as bulk density, soil organic matter (SOM) and pH, are accepted as they provide valuable insights into soil quality and emergence (Bünemann et al. 2018). At this juncture, we provide a pragmatic approach that orients towards achieving healthy soil, but recognising that although soil health assessment, in an integrated way (*sensu* Kibblewhite et al. 2008), is the ideal ambition, we rely on a 'reductionist' soil indicator approach to assess soil health practically.

The EU's evolving definition of soil health highlights a recognition of the ability of soils to sustain ecosystem services, transitioning to a more comprehensive understanding of soil as a vital living system. The EU Mission 'A Soil Deal for Europe' (Mission Soil), aims to improve soil health by identifying and

Summary

- We outline various methods for evaluating soils through frameworks which can be categorised within the broader concept of quality.
- We emphasise the importance of a clearly defined suite of indicators and their interpretation tailored to specific objectives.
- We introduce the methodology of the European Union Soil Observatory (EUSO) and the selection of pan-European indicators as components of the developing draft Directive on Soil Monitoring and Resilience (Soil Monitoring Law, SML).
- We clarify our definition of soil quality and discuss its significance for effective communication and informed decision-making.

addressing soil degradation (Panagos, Borrelli, et al. 2024). This provides one approach (geared towards restoring soils to a minimally acceptable condition) among various frameworks which exist for assessing soil, including soil tilth (the physical condition of soil in relation to its suitability for planting and growing crops) (Karlen 2011); fertility (Blum 2005; Frossard et al. 2006); land capability (Bibby et al. 1991; USDA Natural Resources Conservation Service 2024a, 2024b), and soil security (McBratney et al. 2014). All of these frameworks use indicators to monitor the status and changes in soil resources. They collectively contribute to a more nuanced understanding of soil health and its critical role in sustaining ecosystem services across various spatial scales, functions and stakeholder priorities (Lehmann et al. 2020).

1.2 | Use of Indicators for Soil Health Assessments

Indicators are defined as 'metric(s) derived from parameters that describe the state of the environment, assessing its impact on human beings, ecosystems and materials' (OECD 1993; Faber et al. 2022). Soil indicators, encompassing physical, chemical and biological aspects, serve as the primary means through which frameworks assess soils (Bünemann et al. 2018; Kibblewhite et al. 2008). The selection of soil indicators is undertaken with specific objectives in mind, aiming to reflect the condition or performance of a soil in its capability or capacity to deliver particular functions or ecosystem services. These indicators are frequently used at the field scale to assess whether pH and nutrient concentrations are suitable for cultivating specific crops, and at broader scales, such as nationally, to evaluate soil functionality in the context of constructing new policies (Reynolds et al. 2013; Orgiazzi et al. 2017). No single indicator can provide the entire spectrum of multifunctional characteristics of soils. Therefore, a diverse set of indicators is typically required (Nortcliff 2002).

Previous research highlights the complexity and diversity of soil indicators used for analysis and evaluation, necessary for both habitat-specific and purpose-driven indicators (Bünemann et al. 2018; Ritz et al. 2009; Merrington et al. 2006; Loveland and Thompson 2002; Corstanje et al. 2017). These indicators are essential for accurately reflecting soil conditions and guiding policy development, management practices and interventions (Head et al. 2020). The careful selection and aggregation of relevant indicators are vital for improving policy guidance and promoting sustainable environmental practices (Bünemann et al. 2018).

However, selecting suitable soil indicators on a pan-European scale poses significant challenges; ranging from the variability in climate, topography, geology and soil types, which leads to a different balance of drivers and soil processes across different pedo-climatic zones. Consequently, there is a pressing requirement for the establishment of clear principles and criteria for the selection of soil indicators. Further details on the synthesis of these selection criteria can be found in the Supporting Information provided (Section S1, Tables S1–S5).

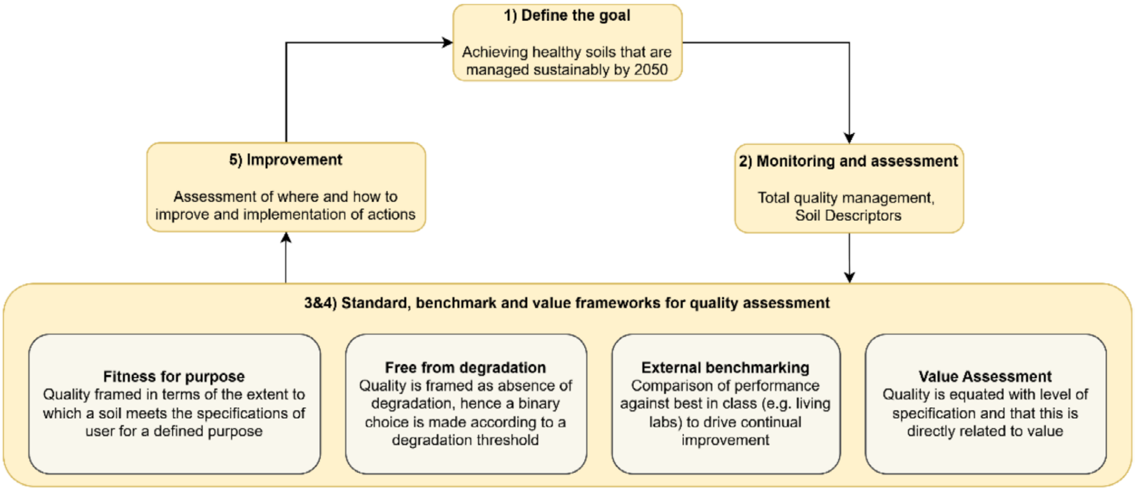
2 | Quality Concepts to Assess Soils

2.1 | The Paradigm of Quality

Quality is a concept that is frequently sought after yet challenging to articulate. The pursuit of quality is a common objective across numerous fields, including education (Cheng and Ming 1997), healthcare (Busse and Panteli 2019), business (Forker et al. 1996), manufacturing (Gunasekaran et al. 1994), and environmental studies (Johnson et al. 1997). The significance of quality lies in its influence on decision-making processes and the actions which follow. These are often guided by how quality is perceived. Harvey and Green (1993) argue that the notion of quality is comparative in two respects: it is contingent upon the evaluator and their perspective. Consequently, the evaluation of quality differs based on who is making the assessment. The authors emphasise that 'this is not a different perspective on the same thing but different perspectives on different things with the same label'. Additionally, interpretations of quality can differ based on particular viewpoints, which may range from absolute or intrinsic quality, to meeting a specific standard or achieving a consistent level. Thus, 'some conceptualisations of quality are rather more 'absolutist' than others' (Harvey and Green 1993). Furthermore, quality is inherently subjective, involving comparisons of what is deemed 'better' or 'worse'. This subjectivity is particularly relevant for soils, as it informs quality framing, operationalization and indicator selection.

The term 'quality' varies in meaning based on the context, which can often result in misunderstandings. It may refer to excellence (the level of distinction or superiority), a standard (the assessment of how good or poor something is) or a characteristic (a specific attribute of an item) (Cambridge Dictionary Online 2024). An aspect frequently overlooked in the drive to streamline to as few soil indicators as possible is that the quality of a soil attribute for one function may not equate to quality for another function. Harvey and Green (1993) provide an in-depth analysis of the quality concept, categorising its applications into five groups: (1) exception, (2) perfection, (3) fitness for purpose, (4) value for money and (5) transformative.

A summary of these categories is presented below, with further details available in Table S6.



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

FIGURE 1 | The total quality management (TQM) framework for continuous improvement and various quality approaches in soil monitoring and management.

- ***Exception***, which can be without a standard (1a). An example of this is often adopted in branding, where, for example, Champagne is viewed as higher quality than other sparkling wine because it comes from the Champagne region of France. Exception can also be with a standard (1b), where the high-quality product exceeds a high standard such as ultra-pure water compared to tap water in a laboratory.
- ***Perfection*** (2), where zero defects (2a) are desirable but not feasible in practice. Therefore, a threshold is set that determines an acceptable level. In the context of water quality, a 'true zero defects' analogy might be zero *E coli* per 100 mL of water, or an acceptable threshold (< 50 mg nitrate/L of water). Another strand of perfection is that of Consistency (2b). This does not rely on analysis of outputs but develops a quality culture at every stage in a process to get things right first time. For example, maintaining all the processes to produce tap water so that it is appropriate for consumption when it comes out of the tap.
- ***Fitness for purpose*** (3), where quality is defined through a function or use, for example, isotonic water may be considered as superior quality to non-isotonic water by an athlete for the purpose of rehydrating the body.
- ***Value for money*** (4), which is related to the level of specification and cost (e.g., bottled water vs. tap water).
- ***Transformative*** (5), where this is characterised by a fundamental change in nature, a qualitative change (e.g., ice turning to liquid water).

Ultimately, the choice of quality category impacts its description, how it is specified, and the techniques, indicators, and their interpretation which are favoured for assessment. Therefore, the definition and category of 'quality' largely determine the approach, criteria, choice of indicator(s) and the required thresholds used to define it. Based on the categories above and in (Table S6), approaches to soil assessment will generally fall into categories (2a), (2b), (3) and (4).

2.2 | Total Quality Management

In previous research, Beckford (2010) discussed the evolution of quality assessment, emphasising a shift towards systems thinking and the integration of total quality management (TQM). This shift in paradigm is crucial for achieving continual quality improvement, as TQM can use various quality framings to improve outcomes. However, Beckford (2010) cautions against reductionism, where focusing on a single aspect may lead to stagnation in quality improvement once a standard is met. Historically, many businesses adopted a reductionist approach in the mid-20th century, but the adoption of systems thinking now encourages a holistic understanding of interactions within a system.

Beckford (2010) highlights that general systems theory, which includes concepts from cybernetics and systems dynamics, leads towards a comprehensive approach to quality. It suggests that all quality framings should be viewed through a TQM lens. This also applies to sustainable soil management as outlined in the Mission Soil which should embrace continual improvement. The various quality concepts outlined in Section 2.1 (2a, 2b, 3 and 4) are contextualised within the framework of TQM illustrated in Figure 1. In this context, the quality objective is: (i) articulated (e.g., the Mission Soil aims to achieve sustainably managed healthy soils by 2050), (ii) identifies the suitable monitoring framework and indicators relevant to the specific quality framework and (iii) improves the execution of actions, typically through recommendations and interventions. The TQM framework aligns with the Drivers, Pressures, State, Impact and Response (DPSIR) model, which is discussed later in this paper. The representations in Figure 1 provide concrete solutions to real-world challenges, often reflecting the viewpoints of many stakeholders.

The Mission Soil aims to standardise TQM, focusing on Living Labs, co-creation and co-design in order to address and overcome barriers (European Commission 2021). Hence, when assessing quality, various aspects need to be considered. These range from: (i) articulating the desired outcomes, (ii) considering how to improve communication, (iii) determining vital stakeholders to communicate with, (iv) identifying the required motivations to effect change, (v) measuring and monitoring the system and (vi) seeking to overcome barriers and constraints. Addressing these challenges is important for making an impact and providing insights which align with the practical objectives of the Mission Soil.

2.3 | Assessment Frameworks in the Context of Soils

Within the TQM framework (Figure 1), four quality framings from Section 2.1 are identified in Boxes 3 and 4 with key characteristics in the table below each row. These are 'Fitness for Purpose' (3, Table S6); 'Free from Degradation' (2a, Table S6); 'External Benchmarking' (2b, Table S6) and 'Value Assessment' (4, Table S6). Each framing addresses a particular problem, and these are explored in subsequent sections.

2.3.1 | Soil Quality in the Context of 'Fitness for Purpose'

The concept of 'fitness for purpose' requires the definition of quality is intrinsically linked to its intended use. This necessitates a clear identification of the purpose, including a specification of the target stakeholders suitable for that purpose. Furthermore, it is essential to establish and demonstrate the criteria for assessing fitness. In the context of soil-related research, initial quality frameworks were primarily focussed on food production, reflecting growers' perspective on purpose. The assessment of fitness was based on the suitability of soil for crop cultivation, one example of which is the development of the Cornell Comprehensive Assessment of Soil Health (CASH) framework (Norris et al. 2020). The evaluation of indicators is grounded in their relevance to crop production objectives. Fitness is quantified by assigning scores between 0 and 100 to soil based on indicators categorised into three groups: 'More is better', 'Optimum curve' and 'Less is better' (Svoray et al. 2015).

In terms of the 'who', Harvey and Green (1993) differentiated fitness for purpose from two viewpoints: that of the customer and that of the institution's mission. In the context of soil, 'customer' can be interpreted as the user (e.g., grower or forester), while 'mission' may be interpreted as the aspect of societal and public goods with respect to the role of soil in providing various ecological and social benefits. Ongoing research aims to develop broader frameworks based on fitness for purpose which account for diverse land uses and the provision of a much wider set of ecosystem goods and services than just agricultural production, for example, soils' ability to store carbon, infiltrate water, support biodiversity, etc. (Robinson et al. 2014; Harris et al. 2023).

2.3.2 | Zero Defects Soil Quality Assessment as 'Free From Degradation'

The 'zero defects' approach emphasises the importance of maintaining soil health through addressing degradation threats (e.g., loss of SOM, pollution, compaction and erosion) (Blum 2004). This approach contrasts with a quality framework that focuses on exceeding high standards. Instead, it defines quality through meeting minimum required standards. In the context of the EU, soil quality is characterised by the absence of significant anthropogenic degradation, as outlined in the EU Soil Protection Framework, which has provided broad consensus among many stakeholders.

Soil degradation threats (e.g., salinization and erosion) are critical factors which can diminish the ability of soil to provide essential ecosystem services (Stolte et al. 2016; Baritz et al. 2021; Hussain et al. 2023; Shokri et al. 2024). These threats adversely affect the physical, chemical and biological characteristics of soil, hindering its optimal functionality. Addressing these challenges has been a longstanding problem for EU Member States and this has been previously articulated in the Thematic Strategy for Soil Protection in 2006 (European Commission 2006). Consequently, the first version of the directive suggested adopting a 'free from degradation' perspective rather than a 'fitness for purpose' approach for pan EU scale.

Currently, the EUSO evaluates soil quality as a binary condition—either soils are degraded or not—based on specific thresholds for soil threats (Panagos, Broothaerts, et al. 2024). A soil that remains within tolerable degradation levels is considered acceptable and does not require restorative measures. However, this framework does not explicitly require a definition of optimal soil quality nor the degree of health, limiting the effectiveness of this approach to a minimum standard. The threat-based approach aligns with the EU's operational concepts, particularly the DPSIR framework (OECD 1993), which assesses the impacts of drivers and pressures on soil condition and informs policy responses aimed at preventing degradation and restoring soil health. The absence of a fitness for purpose approach at pan-EU scale also means that the diverse functional capacities of soils are not formally recognised, and remains an area for future development, especially at more localised scales.

2.3.3 | Value Assessment

Despite its long history, Value Assessment needs to be further developed, as highlighted by Obst et al. (2016). Existing frameworks, such as those for natural capital and green accounting, do incorporate soils. However, these require further refinement, as noted in the SEEA (2024) and by Dominati et al. (2014). The primary objective of these frameworks is to recognise the economic value of soil resources, particularly the services and products they support. Green accounting serves to emphasise the importance of natural capital stocks and the ecosystem services provided by nature, facilitating comparisons between natural solutions and engineered alternatives. The maintenance of natural capital is deemed essential for human economic activity and well-being throughout the EU. This perspective is reflected in the EU's Biodiversity Strategy to 2020 and its 7th Environment Action Programme (European Environment Agency 2019), which explicitly identify the conservation and improvement of natural capital as a key policy objective.

2.4 | External Benchmarking

Benchmarking is a progressive methodology which is viewed as a dynamic element of TQM (Juran and Godfrey 1999). This concept allows for multiple interpretations, necessitating a clear definition of specific intent. These interpretations can be categorised through the following channels: (i) indicating a threshold within a specific population, (ii) serving as one or more objectives or a target derived from the mean, median or other percentiles of a distribution or (iii) establishing external benchmarks for goal-setting, providing a foundation for management objectives based on the achievements of others in comparable situations, each of which is examined further below. This allows for the promotion of ongoing dialogue and continuous improvement of soil conditions (Feeney et al. 2025).

External benchmarking provides context for measurements taken at a specific location by comparing them to similar measurements from equivalent soils under the same land use and management practices. This differs from target setting scenarios (i) and (ii), which could lead to undesirable outcomes, such as conforming to the average of a population of degraded soils. Soil managers can assess the position of their soils within a broader population, providing relevant context. This allows them to identify whether their soils fall at the lower or upper end of the desirable range. If they find themselves at the lower end, they can investigate the underlying causes and pursue improvements. By establishing realistic and achievable goals, they can foster a cycle of monitoring and continuous improvement. The fundamental concept of external benchmarking is based on the belief that the established goals are attainable, given that they have been successfully met by others operating in comparable environmental conditions. In the context of local soil management, this methodology seeks to mitigate the adverse effects linked to inflexible targets (Matson et al. 2024) and redirect the conversation and culture towards strategies for continual improvement.

External benchmarking serves as an alternative approach to ensuring consistency (2b) in the sense of developing a quality-centred culture which is frequently adopted by practitioners. In this context, benchmarking proves beneficial for soil managers, enabling them to assess their soil performance indicators (e.g., soil organic carbon [SOC]) in relation to similar indicators gathered by other soil managers dealing with comparable soils and land uses. Figure 2 illustrates the results produced using a benchmarking tool (SOD 2024; Feeney et al. 2023, 2024). The distribution in this figure is provided for medium-textured loamy soils under arable management. The solid blue line represents a measurement for a farm field on the same soils taken by a soil manager. The performance is typical but falls below the median and indicates substantial room for improvement. It is then the responsibility of the soil manager to analyse their practices, compare with others and consider improvements to move themselves progressively up the distribution. Through analysis of the performance of soil indicators (categorised as below typical, typical and above typical) and comparing them with those performing at a higher level (above typical), soil managers can identify best practices and implement strategies for continuous improvement.

In this framework, benchmarking is inherently connected to a specific landscape type as well as a designated time period. There is a consensus that adopting a combination of benchmarks and goal setting for management provides a robust, practical and insightful methodology. This has been recently

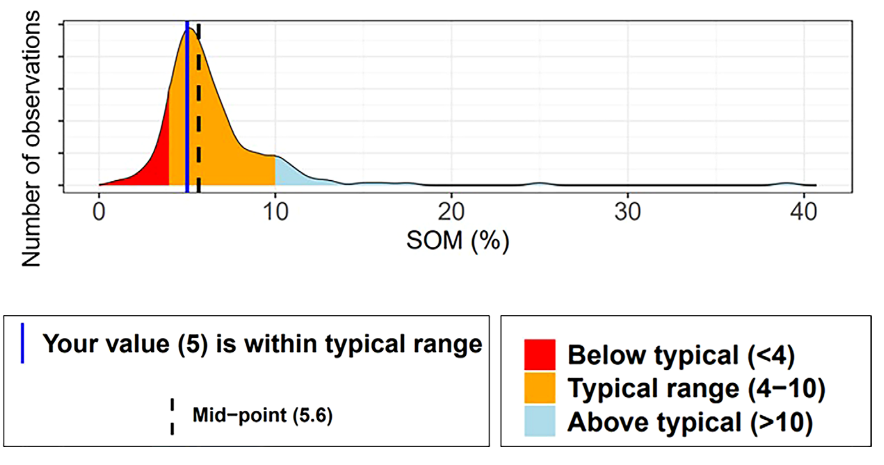


FIGURE 2 | Example output from the soil fundamentals (SOD) tool (SOD 2024), as outlined in Feeney et al. (2023), illustrating soil organic matter (SOM) distribution. The data represents a medium loam soil under cropland management, derived from the UK Countryside Survey monitoring dataset (Robinson et al. 2024). In the graph, the blue vertical line marks a value of 5, which falls within the typical range. The black dotted line indicates the mid-point value of 5.6. The red section of the curve shows SOM levels below the typical range, the orange section represents the typical range and the blue section indicates values above typical based on the data collected to date.

implemented across Europe (Drexler et al. 2022; Feeney et al. 2023; Gutierrez et al. 2024). External benchmarking serves as a holistic approach to goal setting, effectively aligning immediate performance objectives with overarching improvement strategies. Benchmarking can be forward-looking by using modelling methods to estimate the 'maximum achievable level' of soil indicators under optimal management conditions, providing aspirational benchmarks that guide long-term improvement. Modelling also enables scenario testing, helping soil managers evaluate the impacts of different practices and identify areas for potential improvement. When combined with external benchmarking, modelled results can highlight knowledge gaps by revealing practices that exceed expected performance. However, the effectiveness of modelling varies by indicator stability, being more suitable for stable metrics like soil organic carbon (SOC) and more challenging for variable indicators such as soil nutrient losses.

As discussed, various methods for conceptualising soil quality are available. Nevertheless, it is important to note that there is no definitive 'correct' or 'incorrect' viewpoint of implementing different frameworks.

3 | Indicator Selection

Identifying and addressing societal challenges and policy questions can provide appropriate context for monitoring soils. One of the overarching frameworks used by policy makers within the EU to assess such activities and address important environmental challenges is the drivers, pressures, state, impact and (societal) response model of intervention (DPSIR) framework (Figure 3). This framework aligns with TQM described earlier in the paper.

3.1 | Policy and Asset Management: The Role of the DPSIR Framework

The DPSIR framework was designed to describe relationships and interactions between society and the environment (Gabrielsen and Bosch 2003). It is a conceptual model which has previously been adopted by the European Environment Agency (EEA) to assess the pressures and risk of failing to meet environmental quality objectives (Hall and Voulvoulis 2008). It has also been used for a range of other activities such as assessing pressures from agricultural land use and evaluating the impacts of this on surface water, ground water and pollution (Giupponi and Vladimirova 2006; Bradley and Yee 2015). Over time, DPSIR has extended to further improve understandings between driving forces, pressures, states, impacts and responses (extension of the PSI model developed by OECD 1993) (EEA 2023).

3.2 | Indicators as Part of the DPSIR Framework

The DPSIR framework is evaluated by investigating a range of soil indicators which can provide the foundations to subsequent research and analyses. These indicators are associated with measures related to environmental pressures (*P*); indicators connected to environmental conditions which correspond to a state (*S*), and indicators which are connected to a society and

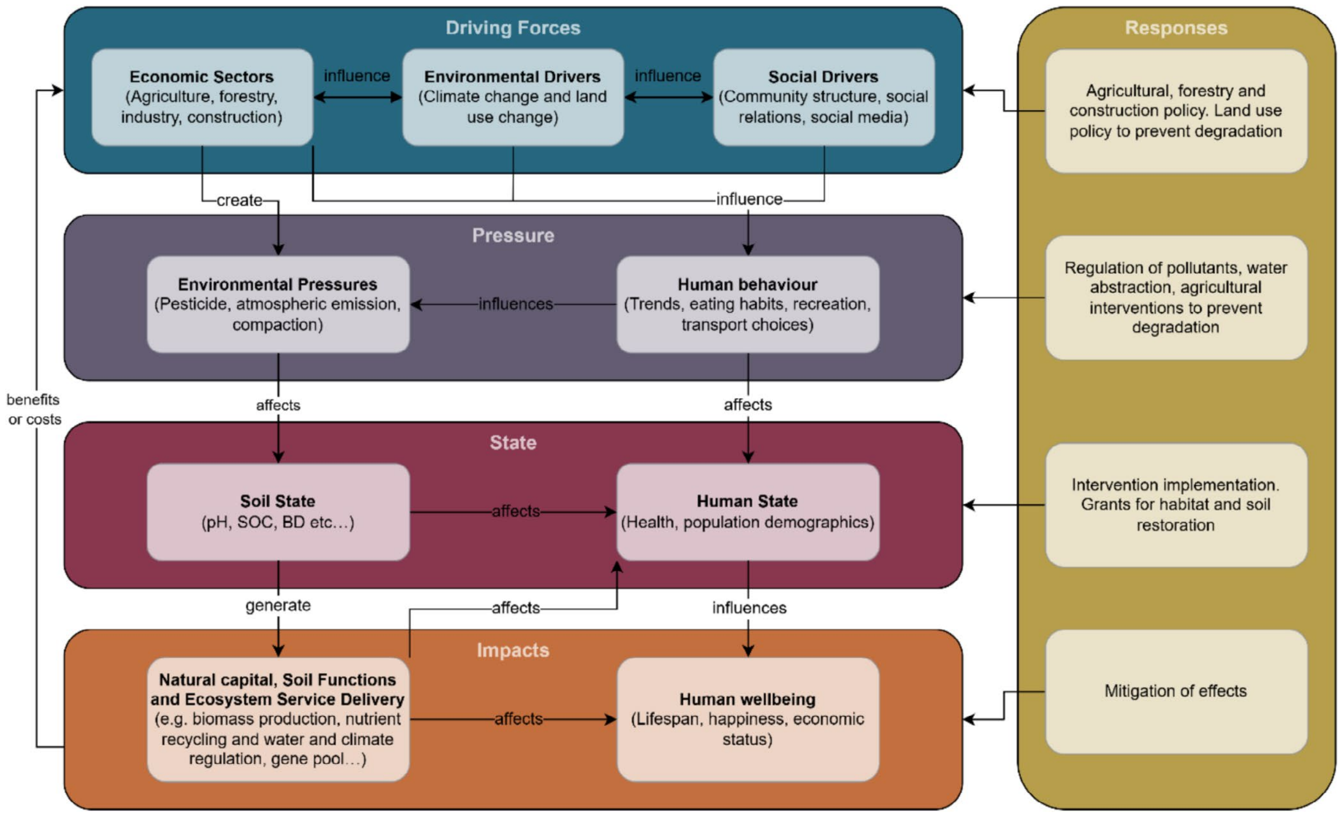


FIGURE 3 | The drivers, pressures, state, impact and (societal) response model of intervention (DPSIR) conceptual framework (adapted from Bradley and Yee 2015).

their response(s) to environmental change(s) (*R*). These can be individual or collective actions to help adapt, mitigate or even prevent human-induced negative impacts on the environment. Moreover, these can be used to halt or reverse already inflicted environmental damage.

Indicators can be further categorised according to a temporal chronology. This considers leading (inputs), concurrent (process conditions) and lagging (outcomes) indicators (Juran and Godfrey 1999). For example, in the context of soil organic carbon (SOC), a leading indicator might be the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). This provides the energy bound for primary production of SOM by plants, which can potentially drive the soil food web. A concurrent indicator might describe the redox status of the soil, and a lagging indicator is soil carbon concentration, the outcome of the system inputs and processing.

Using such a framework, condition (state) lagging indicators are assessed in relation to the SML list of descriptors, emphasising the need for a logical sieve selection tool or expert knowledge to identify metrics associated with leading, concurrent or lagging indicators. It highlights that these indicators may show varying levels based on their status—whether they are established indicators, limited in scope or still under development. In this regard, the Inter-Agency and Expert Group on Sustainable Development Goals (IAEG-SDGs) introduced a tiered system for soil indicators in their 2019 report (SDG Reporting 2024). This is further elaborated in Section S3.

The DPSIR framework requires careful consideration of various factors to ensure that selected indicators effectively address soil threats and inform future policies. Initially, the OECD (1993) and Lehmann et al. (2020) identified three primary factors for selecting appropriate measures: policy relevance, analytical soundness and measurability. This foundational approach was further refined by UKSIC (Merrington et al. 2006) and Bone et al. (2014), which introduced additional criteria for evaluation. A comprehensive set of criteria has been synthesised in the Supporting Information, culminating in an indicator table (Table S1) that aligns with previous templates established by Black et al. (2008).

4 | Indicator Selection in the Context of the Mission Soil

Launched in 2019, the EU Green Deal highlights the vital role of healthy soils in achieving various environmental and agricultural targets, including sustainable farming, biodiversity restoration and climate neutrality (Panagos et al. 2022; Montanarella and Panagos 2021). The EU Soil Strategy for 2030 and the proposed SML are significant milestone advancements in soil protection efforts within EU policy. The EU Mission 'A Soil Deal for Europe' (Mission Soil) aims to enhance soil health and sustainable land management through the establishment of 100 Living Labs and Lighthouses, which will facilitate innovation and knowledge sharing regarding soil health.

To support these ambitious goals, a systematic and harmonised soil monitoring framework is essential at EU level, accompanied by measurable indicators that assess soil health. This framework is critical for identifying areas requiring remediation and evaluating the effectiveness of restoration actions. The 'free from degradation' framework is deemed suitable for pan-European assessments, while a 'fitness for purpose' approach is recommended for localised management strategies (Stone et al. 2016). These measures are intended to inform policymakers about necessary interventions and enhance soil health across the EU.

The EU Soil Observatory (EUSO), hosted by the European Commission's Joint Research Centre (JRC), has introduced the EUSO Soil Degradation Dashboard (European Union Soil Observatory (EUSO) 2024; Panagos, Broothaerts, et al. 2024). This tool serves to monitor soil conditions across the EU using a set of 19 carefully selected indicators (Table 1). These indicators are based on their relevance and data availability, reflecting key soil degradation processes identified in scientific literature (e.g., Bünemann et al. 2018; Stone et al. 2016). Each indicator has defined EU-wide thresholds that determine whether soils are classified as degraded or non-degraded, adhering to a 'one out, all out' principle which aligns with a free-from-degradation approach.

The dashboard represents a significant development in the spatial assessment of soil health at the EU level, providing valuable insights for policymakers regarding areas that require intervention to maintain soil health. While inherent uncertainties with the dashboard have been acknowledged (Panagos, Broothaerts, et al. 2024), it is positioned as a crucial tool for informing future actions. Future plans for the dashboard include regular updates to enhance the assessment of soil degradation processes (Prăvălie et al. 2024), with the addition of new indicators addressing challenges such as diffuse pollution and biodiversity. Furthermore, existing indicators will be refined to account for varying pedo-climatic conditions, leading towards collaboration with Mission Soil funded projects to ensure comprehensive and accurate monitoring (see also Panagos, Borrelli, et al. 2024; Panagos, Broothaerts, et al. 2024).

5 | Current and Future Development Under the Mission Soil

As a result of the SML, new data and information on soil indicators will become available as well as new data collected from current and future Mission Soil projects, further LUCAS surveying campaigns (Land Use/Cover Area Frame Survey soil module; Orgiazzi et al. 2017) and reporting data from Member States. Living Labs created within the Mission Soil, alongside established soil monitoring programs, have an important role to play, as they can provide best-practices for sustainable land and soil management from the bottom up and may seek to apply 'fitness for purpose' approaches such as score cards or 'external benchmarking' to improve the health of soil (Figure 1). This may also include additional or more bespoke indicators (Stone et al. 2016).

The work presented here emphasises the importance of understanding various frameworks to optimise their application and integration in practice. The 'free from degradation' approach is particularly effective at large scales, such as national levels, while the 'fitness for purpose' framework is also more

TABLE 1 | Soil degradation indicators included in the EUSO Soil Degradation Dashboard with their respective thresholds and data sources.

Soil degradation processes	Indicator	Threshold	References
Soil erosion	Water erosion	Erosion rate > 2 t ha^{-1} $year^{-1}$	Panagos et al. (2020)
	Wind erosion	Erosion rate > 2 t ha^{-1} $year^{-1}$	Borrelli et al. (2017)
	Tillage erosion	Erosion rate > 2 t ha^{-1} $year^{-1}$	Borrelli et al. (2023)
	Harvest erosion	Erosion rate > 2 t ha^{-1} $year^{-1}$	Panagos et al. (2019)
	Post fire recovery	Recovery rate < 1	Vieira et al. (2023)
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 nutrients	Nitrogen surplus	Agricultural areas where N surplus > 50 kg ha^{-1} $year^{-1}$	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 organic carbon (SOC)	Distance to max SOC level	Distance to max SOC level > 60%	De Rosa et al. (2024)
Loss of soil bio-diversity	Potential threat to biological functions	≥ Moderately-High level of risk	Orgiazzi et al. (2016)
Soil compaction	Packing density	Packing density ≥ 1.75 g cm^{-3}	Panagos, De Rosa, et al. (2024)
Salinization	Secondary salinization risk	Areas in Mediterranean region where > 30% is equipped for irrigation	Siebert et al. (2013)
Loss of organic soils	Peatland degradation risk	Peatlands under hotspots of cropland	UNEP (2022)
Soil sealing	Built-up areas	No threshold (all built-up areas)	Copernicus (2018)

Source: Available from: https://esdac.jrc.ec.europa.eu/euso/euso-dashboard-sources.

appropriate at the local level. External benchmarking, which involves using distributions to establish context and goals, is more versatile and applicable across multiple scales, facilitating the integration of different approaches. Additionally, valuation methods, such as green accounting to payments for ecosystem services, are also multiscale and provide valuable insights which extend beyond soil science to address ecological trade-offs comprehensively. Overall, these frameworks can be adaptable to many scales, stakeholders and objectives, highlighting their multifaceted utility. The challenge, however, is to bring them together into a seamless tool set, preferably through an online and interactive platform, to enhance accessibility and soil literacy in line with the Mission Soil. An approach to help stakeholders assess soils is required that perhaps begins with field observation, using a spade as necessary, before resorting to standard laboratory analysis and more sophisticated diagnostics if needed. This still needs to be developed.

Currently, the EUSO Soil Degradation Dashboard reveals that over 62% of EU soils are experiencing some form of degradation (Panagos, Broothaerts, et al. 2024), with many soils affected by multiple degradation types. The primary issues identified include a loss of soil biodiversity affecting 33% of the EU, water erosion impacting 19% and a reduction in soil organic carbon (SOC) affecting 14%. Certain indicators, such as post-fire recovery and peatland degradation risk, have limited data coverage, while others, like tillage and harvest erosion, are restricted to arable areas. Among the areas with available data, the highest rates of unhealthy soils are observed in post-fire recovery (75%), loss of SOC (53%) and loss of soil biodiversity (37%). The Mission Soil projects aim to improve the EU's soil indicator frameworks by employing quality approaches, thereby establishing effective communication pathways to engage stakeholders, including policymakers and practitioners like farmers and foresters, in promoting healthy soil practices.

The collaboration effort centres on three primary areas of focus, with the first being the refinement and updating of indicator-related datasets. As new datasets emerge, both the indicator list and the EUSO Soil Degradation Dashboard will be updated concurrently. The initial emphasis will be on developing indicators which require enhancement, particularly soil water holding capacity, while also addressing significant knowledge gaps such as soil biodiversity, diffuse pollution and organic contaminants like Polycyclic Aromatic Hydrocarbons (PAHs) and Benzene, Toluene, Ethylbenzene and Xylenes (BTEX) compounds. Additionally, the collaboration will tackle emerging issues, including microplastics and Per- and Polyfluoroalkyl Substances (PFAS), as well as subsoil compaction, as outlined in the Mission Soil Implementation Plan and the descriptors in the SML. Currently, many indicators from the Mission Soil Implementation Plan and descriptors from the proposed SML are being integrated into the existing EUSO Soil Degradation Dashboard. However, these indicators are expected to undergo further development and updates in the coming years, driven by enhanced data availability and increased scientific collaboration.

Secondly, the development of accepted indicator thresholds for quality frameworks is essential, requiring refinement based on local factors such as soil type, climatic context and land cover. Tailoring these thresholds to local conditions and quantifying the interactions among indicators can significantly reduce uncertainties and improve the relevance of the indicator framework. Successful implementation will depend on integrating recent research findings from initiatives like the Mission Soil, particularly those derived from field experiments and assessments. Furthermore, the Mission Soil is expected to generate new research and propose indicators that will inform the revision of the SML post-2036, reflecting advancements in knowledge. Additionally, the current binary approach to assessing soil degradation should transition to a more nuanced extent mapping method, which considers the distribution and severity of soil threats, providing a more comprehensive understanding of soil health.

Finally, though there is not yet consensus in the soil science community, the development of a composite soil health index has been proposed as a critical area of focus (Lehmann et al. 2020). Such an index would aim to integrate various individual soil health indicators into a unified value or range. An initial attempt at creating such an index is documented by Prăvălie et al. (2024). It is important to recognise that soils experiencing multiple degradation processes will obtain different index values compared to those affected by a single process, necessitating consideration of the severity of degradation. The formulation of these indexes should examine the significance of each indicator and its compliance with established thresholds. Furthermore, incorporating pedo-climatic conditions is essential for achieving a comprehensive understanding of soil health across the EU and its Member States. Ultimately, this composite soil health index has the potential to serve as an effective communication tool for policymakers and the public.

Figure 4 illustrates the various efforts that can contribute to the overarching goal of sustainably managing healthy soils by 2050. It highlights the progress made since 2012, when, at the time, the focus was on a degradation-free approach. This progress has led to the creation of the EU Soil Observatory and the EUSO Soil Degradation Dashboard. Through continuous engagement with EU Mission Soil projects and the development of ongoing Living Labs, EU soil science can effectively collaborate and incorporate quality frameworks, leading to better use of the EU SML. The figure (adapted from Panagos et al. (2022); Panagos, Borrelli, et al. (2024)) attempts to show the development of these multiple efforts including quality frameworks and indicate how they will all contribute to the goal of achieving sustainably managed, healthy soils by 2050.

Although soil protection efforts have led to the development of 'free-from-degradation' approaches, primarily at national and European levels, these methods still need further development and refining. For local-level management, the 'fitness-for-purpose' and 'external benchmarking' approaches also require further development within current Mission Soil activities. Various approaches are being tested and ongoing, with Matson et al. (2024)'s work showing examples of this. Value approaches

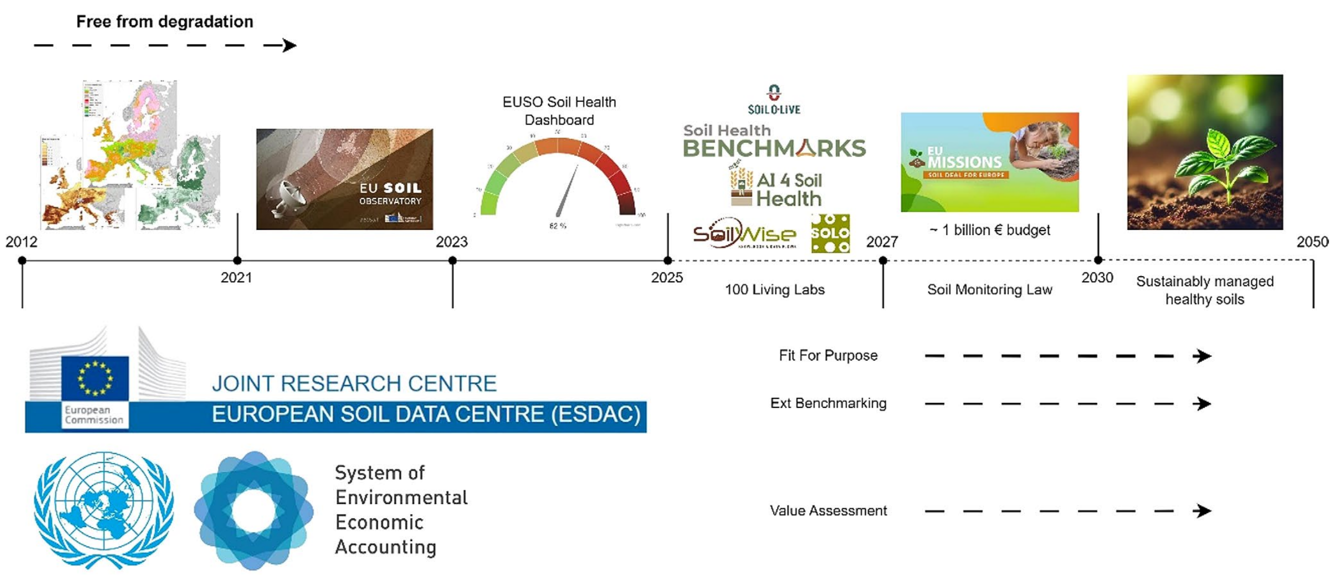


FIGURE 4 | Timeline representing key stages of development of the Mission Soil in the EU adapted from Panagos, Borrelli, et al. (2024). Quality framework development is added with the purpose of achieving sustainably managed healthy soils by 2050. Value assessment is developing concurrently under United Nations green accounting efforts (SEEA 2024).

are being developed as part of the EU's commitment to natural capital accounting (European Environment Agency 2019) and the System of Environmental and Economic Accounting (SEEA 2024).

6 | Conclusions

This review has outlined the absence of a uniform definition of quality and has emphasised the utility of various interpretations. Moving forward, the selection and interpretation of indicators will be critical, as this will be influenced by the chosen framework. Given Europe's diversity in climate, topography, geology and soil types, establishing clear principles and criteria for selecting appropriate indicators is essential. Quality and soil frameworks are divided into four primary approaches: fitness for purpose, absence of degradation, external benchmarking and value assessment. Three key challenges for the future are identified: (i) the necessity to refine and update datasets related to indicators in the European Union Soil Observatory (EUSO), (ii) the establishment of accepted thresholds for indicators or methods for scoring continuous indicators, coupled with their interpretation within the relevant quality framework to ensure flexibility regarding land use, habitat or soil type and (iii) the creation of a composite soil index that encompasses the extent and severity of quality, health or degradation. Clearly presenting the concept of quality is essential for effective communication and informed decision-making, as well as for ensuring that resource allocation and subsequent actions are properly managed. As the Soil Monitoring Law develops and monitoring occurs at various scales, the creation of fitness-for-purpose assessment tools for soil managers, such as scorecards or soil benchmarking, will be increasingly important for examining soils at local levels, with the ultimate aim towards achieving healthy soils throughout the EU by 2050.

Author Contributions

Grant A. Campbell: conceptualization, writing – original draft, writing – review and editing, visualization. **Pete Smith:** funding acquisition, writing – review and editing. **Nils Broothaerts:** writing – review and editing, writing – original draft. **Panos Panagos:** conceptualization, writing – review and editing. **Arwyn Jones:** writing – review and editing. **Cristiano Ballabio:** writing – review and editing. **Daniele De Rosa:** writing – review and editing. **Lis Wollesen de Jonge:** writing – review and editing. **Emmanuel Arthur:** writing – review and editing. **Lucas Gomes:** writing – review and editing. **Nima Shokri:** writing – review and editing. **Mehdi Afshar:** visualization. **Gergely Tóth:** writing – review and editing. **Peter Lehmann:** writing – original draft, writing – review and editing, conceptualization. **Pasquale Borrelli:** writing – review and editing. **Christine Alewell:** writing – original draft, writing – review and editing, conceptualization. **Robert Minarik:** writing – review and editing. **Tomislav Hengl:** writing – review and editing. **Ichsani Wheeler:** writing – review and editing. **Lindsay Maskell:** writing – review and editing. **Madlene Nussbaum:** writing – review and editing. **Laurence Jones:** writing – review and editing, conceptualization. **Christopher J. Feeney:** writing – review and editing. **David A. Robinson:** writing – original draft, conceptualization, funding acquisition, writing – review and editing, visualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting information.