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Advancing nature-based solutions through enhanced soil health monitoring in the United Kingdom

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Abstract

Soil health is a critical component of nature-based solutions (NbS), underpinning ecosystem multifunctionality and resilience by supporting biodiversity, improving carbon sequestration and storage, regulating water flow and enhancing plant productivity. For this reason, NbS often aim to protect soil health and restore degraded soil. Robust monitoring of soil health is needed to adaptively manage NbS projects, identify best practices and minimize trade-offs between goals, but soil assessment is often underrepresented in NbS monitoring programmes. This paper examines challenges and opportunities in selecting suitable soil health metrics. We find that standardization can facilitate widespread monitoring of soil health, with benefits for stakeholders and user groups. However, standardization brings key challenges, including the complexity and local variability of soil systems and the diverse priorities, skills and resources of stakeholders. To address this, we propose a flexible, interdisciplinary approach combining soil science, ecology and socio-economic insights. We introduce an interactive tool to help users select suitable soil and biodiversity metrics, which are context and scale-specific, and suggest avenues for future research. We conclude that integrating soil health into NbS through new and improved monitoring approaches, newly available datasets, supportive policies and stakeholder collaboration can enhance the resilience and effectiveness of NbS, contributing significantly to global sustainability goals.

KEYWORDS

ecosystem multifunctionality, ecosystem resilience, nature-based solutions, nature-based solutions monitoring, soil health, soil health monitoring

1 | INTRODUCTION

There is growing interest from a range of ecologists, soil scientists, landowners, policy makers and other stakeholder groups in applying nature-based solutions (NbS) to tackle the intertwined ecological and climate crises while meeting the needs of a growing human population (Seddon et al., 2020). NbS are defined by the United Nations as 'actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits' (United Nations Environment Assembly, 2022). The European Commission adds that NbS are 'inspired and supported by nature', are cost-effective and help to build resilience (European Commission, 2023). A key feature of NbS is that they use holistic approaches to support multiple positive outcomes for people and nature (Cohen-Shacham et al., , Seddon et al., 2019; Warner & Warner, 2022; Welden et al., 2021).

NbS encompass many actions, such as safeguarding and sustainably managing both natural and semi-natural environments, integrating green spaces in urban areas, and adopting nature-based practices for farming (Seddon et al., 2019). They have increasingly gained political traction as a potential means of delivering climate change mitigation (Donatti et al., 2022; Fawzy et al., 2020; Girardin et al., 2021), adaptation (Chausson et al., 2020; Kabisch et al., 2016; Seddon et al., 2020), food security (Cassin & Matthews, 2021a; Zhu et al., 2023), water security (Cassin & Matthews, 2021b; Cooper, 2020; Everard et al., 2020; Mishra et al., 2021) and disaster risk reduction (de Jesús Arce-Mojica et al., 2019; Debele et al., 2023).

As policy interest in NbS for climate change grows, there is a greater emphasis on accountability and transparency to ensure that NbS are underpinned by, and provide genuine benefits for, biodiversity, simultaneously maximizing their holistic benefits for nature and people (Donatti et al., 2022; Seddon et al., 2021). The foundation of NbS lies in the understanding that well-functioning ecosystems offer numerous essential services critical for human well-being, such as carbon sequestration, flood management, shoreline and slope stabilization, and provision of clean air and water, food, fuel and medicinal resources (Seddon et al., 2020). Many of these services are underpinned by healthy soils, yet most of the world's soils are degraded, and soil erosion is likely to increase up to 60% in the next 30 years (Borrelli et al., 2017). NbS can play a key role in safeguarding and restoring our soils for future generations in many ways, such as through soil–water conservation methods in farming, peatland restoration and reforestation on erosion-prone slopes. Yet while the importance of monitoring and supporting overall ecosystem health in NbS has been highlighted (Key et al., 2022), the specific role of healthy soils in delivering sustainable NbS and the effectiveness of NbS in supporting soil health have received less attention. Explicitly including soil health as an additional objective in many NbS projects would lead to a more integrated approach that considers both the above- and below-ground components of ecosystem functioning and services simultaneously.

In this paper, we discuss the importance of integrating soil health within NbS planning and monitoring. We present general principles drawn from global research and consider how these could be integrated into policy and practice in the context of the UK of Great Britain and Northern Ireland (UK), where new agri-environment policies to support soil health are in development and approaches to soil monitoring are fairly well advanced. Despite this UK focus, many of our findings will be widely applicable. Notably, we:

- Provide evidence of how soil health underpins successful NbS delivery, including resilience and multifunctionality;
- Assess the current state of research on soil health monitoring, explore the challenges and opportunities related to development of standardized soil health metrics to enable more widespread monitoring in NbS projects and highlight emerging technologies for future soil health monitoring;
- Discuss opportunities for integrating soil health monitoring into NbS activities; and
- Provide recommendations on policy frameworks and incentives to promote soil health within NbS, and suggest areas for future research.

2 | METHODS

This review follows a narrative approach, synthesizing evidence from peer-reviewed literature, government reports, policy documents and case studies on literature on the integration of soil health within NbS. Relevant studies were identified through targeted searches in databases such as Web of Science, Google Scholar, Scopus and Google using key terms like 'soil health', 'soil quality', 'soil ecosystem services' 'soil functions', 'soil monitoring', 'sustainable land management' 'nature-based solutions' 'ecosystem services', 'sustainable development goals' and 'climate change mitigation/adaptation'. The review primarily focuses on research published from 2000 to 2023, with an emphasis on both global and UK-specific studies. Selected literature was chosen based on its relevance to soil health in the context of NbS, the role of soils in supporting ecosystem services and the potential of soil health monitoring to improve NbS outcomes, guided by the authors' expertise and with the aim of capturing diverse perspectives from ecology, agriculture and environmental policy. The themes explored in this review, such as soil health monitoring, the role of soils in ecosystem services and the integration of soils within NbS, were identified both inductively from common trends in the literature and deductively, based on gaps in previous reviews recognized by the authors. This approach allowed for the exploration of key trends, challenges and opportunities, while also identifying gaps in the current knowledge base.

3 | HOW SOIL HEALTH UNDERPINS NbS

The term 'soil health' was first coined during the 1910s (Brevik (2018)) and has been particularly widely applied since the 1990s (Harris et al., 2022; Powlson, 2020), but with different connotations depending on the context and target audience. The Intergovernmental Technical Panel on Soils (ITPS, 2020) define it as 'the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems'. The term soil health is often used synonymously with soil quality, commonly 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 health' (Doran & Parkin, 1994). However, while both soil quality and soil health are framed in anthropocentric terms, focusing on the benefits to humans (Lal, 2016), soil health is a broader concept extending beyond human interests. In essence, it reflects the continued capacity of soils to support ecosystem sustainability, considering the overall functioning and resilience of the soil ecosystem and wider sustainability goals (Veerman et al., 2023).

Soils are part of a dynamic and complex system which forms the foundation of terrestrial ecosystems. Soil consists of physical, chemical and biological aspects (Bünemann et al., 2018). Physical properties encompass pores, aggregates and structures that allow movement of air and water for gaseous exchange and provide habitat for soil organisms. Chemical properties moderate the availability and transformation of chemical components, including those providing energy and nutrition. Biological aspects include biological diversity (ranging from within-species genetic diversity to cross-taxon soil community composition), and the resulting biochemical and biophysical processes. Together, these properties interact to provide many essential ecosystem services and functions: regulating and cycling water, carbon and nutrients, supporting the growth of plants and providing habitat for many species, from microorganisms to larger fauna. In healthy soils, these properties help to create environments that are conducive to flourishing above and below-ground ecosystems (Hou, 2023; Lal, 2016).

Thus, healthy soils are a vital component of successful NbS, supporting a wide range of interdependent functions which underpin ecosystem service provision in both agricultural and semi-natural habitats, and are essential for the sustainable development of human societies (Kopittke et al., 2024; Smith et al., 2021) (Figure 1). In addition, healthy soils contribute to the stability, productivity and sustainability of ecosystems by enhancing adaptation and resilience to environmental change (Lal, 2016).

Healthy soils can play a key role in delivering the Sustainable Development Goals (SDGs), adopted by the United Nations in September 2015 (Colglazier, 2015). All 17 SDGs can be directly or indirectly linked to soil (Figure 1), with the strongest links for alleviating poverty (SDG 1), ending hunger (SDG 2), improving health (SDG 3), providing clean water (SDG 6), affordable and clean energy (SDG 7), industry innovation and infrastructure (SDG 9), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), economic growth (SDG 8), climate action (SDG 13) and life on land (SDG 15) (Lal et al., 2021; Smith et al., 2021). Given these connections, and the complex and strong link between climate change, soil degradation and food insecurity (Lal, 2014), integrating soil health within NbS emerges as a strategic approach to meet the SDGs.

Most obviously, soils directly or indirectly produce 98.8% of the food we eat (Kopittke et al., 2019). Soil health is important for supporting high crop yields, whilst minimizing the use of fertilizers and pesticides (Montgomery et al., 2024), thus ensuring food security (SDG 2) and producing more nutritious foods which support human health (Kopittke et al., 2024) (SDG 3). Microorganisms in healthy soils break down organic matter, releasing essential nutrients, such as nitrogen, phosphorous and potassium into the soil to help plants grow. Thus, nutrient cycling underpins the productivity of ecosystems, which also makes them more resilient and capable of recovering from anthropological disturbance. Soil health has a key role to play in NbS for improving the sustainability of agriculture, as it minimizes the need for external inputs, diminishes nutrient depletion from the soil, extends the timeframe for soil cultivation, optimizes soil porosity for enhanced water retention during dry conditions and improves drainage during wet periods (Griffiths et al., 2018). NbS such as restoring degraded lands and implementing sustainable agricultural practices can improve soil fertility (Altieri & Nicholls, 2003) and biodiversity (Dobson et al., 1997) (SDGs 2, 15), reduce poverty by increasing agricultural productivity (Tahat et al., 2020) (SDG 1) and foster sustainable economic growth by increasing farm incomes (SDG 8) (Breure et al., 2018).

Soils are also critical for climate change mitigation, storing three times as much carbon as the atmosphere (SDG 13) (Lal, 2010). Healthy soils which are rich in organic matter and have active microbial communities are more effective at storing and sequestering carbon (Don et al., 2024; Fawzy et al., 2020; Smith, 2004). Protecting

FIGURE 1 Functions provided by soils (inner ring), the Nature's Contributions to People (NCP) provided by soils underpinned by these functions (middle ring) and impacts on the SDGs through the NCP supported by soils (outer ring). Light blue numbered circles in the middle ring show the corresponding soil functions that contribute to the NCP. Grey numbered circles in the outer ring show the corresponding NCP that contribute to the SDGs. Figure taken from Smith et al. (2021).

the vast carbon stores in peatland and restoring degraded peat soils is crucial for reducing carbon dioxide emissions (Evans et al., 2017). As well as sequestering carbon directly, healthy soils are fundamental to the success of ecosystem restoration for climate change mitigation, such as reforestation (Reyer et al., 2009) and wetland restoration (Taillardat et al., 2020).

NbS also depend on healthy soils to filter and store water, maintaining water quality and availability (SDG 6) as well as regulating hydrological flows. Soil condition influences evaporation, infiltration and surface runoff, and this can be crucial for NbS such as natural flood management, riparian buffers and wetland restoration, which aim to moderate flow rates and filter pollutants (Cooper, 2020). Healthy soil, that is well-structured (featuring significant pore-space containing air and water between soil particles) and with ecologically appropriate vegetation cover, is also less prone to erosion and landslides. It can therefore help to maintain water quality by preventing sediments and pollutants from entering waterways, thus also reducing sedimentation in reservoirs which affects the output of hydro-electric plants (Issaka & Ashraf, 2017).

NbS must deliver benefits for biodiversity (SDG 15), and biodiversity in turn underpins the benefits delivered by NbS and confers resilience to change (SDG 13) (Seddon et al., 2021). Soils can provide habitats for a range of organisms, such as microbes, invertebrates and small mammals, which together are crucial for soil fertility and the broader ecosystem (Guerra et al., 2021; Lavelle, 2013). The enormous genetic diversity of soil organisms, which we are only beginning to understand, also holds immense potential for pharmaceutical and biotechnological innovation (Wall et al., 2015) to support human health (SDG 3). Soil health directly influences the health and diversity of plants, which form the base of terrestrial food webs (Costantini & Mocali, 2022) and provide habitat for a wide range of organisms, supporting a stable ecosystem that can sustain rich biodiversity above and below ground (Gatica-Saavedra et al., 2023; Guerra et al., 2021; Köninger et al., 2022). Healthy soils are also known to buffer plants against environmental stresses, including those resulting from climate change (SDG 13), such as droughts, waterlogging, pests and diseases (Naz et al., 2023), as well as directly reducing the impact of extreme weather conditions by absorbing excess rainfall to reduce flood risk and storing water for use during droughts (Issaka & Ashraf, 2017).

Improving soil health can deliver synergies across multiple environmental and socio-economic benefits. For example, well-managed soils, rich in organic matter, can enhance water-holding capacity, store and sequester more carbon, reduce erosion, support biodiversity, and increase soil fertility and productivity (Baritz et al., 2021; Bossio et al., 2020; Haygarth & Ritz, 2009; Powlson et al., 2011). This provides socio-economic benefits by, for example, supporting more profitable and resilient farming systems (Rojas et al., 2016), or improving water quality and thus reducing the need for expensive water treatment (SDG 6). Integrating water and soil conservation measures also results in demonstrable positive outcomes. For instance, the Upper Tana-Nairobi Water Fund, n.d., which assists farmers in adopting practices such as vegetation buffer zones, agroforestry, terracing, reforestation and grass buffer strips to improve water quality and soil health, is projected to generate up to USD 21.5 million in savings from water treatment, increased power generation, and higher yields for both small and large-scale farmers over 30 years (Cooper, 2020). These practices reduce soil erosion, enhance water infiltration and decrease sediment runoff, benefiting both soil fertility and water quality. They are supported by monitoring and data collection systems that measure changes in water quality (e.g. turbidity and total suspended solids) ensuring that the interventions are having the desired effects on both soil and water resources (Upper Tana-Nairobi Water Fund, 2022). According to Inamdar et al. (2023) soil health is often overlooked in current stream and floodplain restoration projects, which could result in restoration efforts not achieving their full potential. This is partly due to the absence of guidelines and metrics addressing soil health.

Soil health thus governs the health of entire landscapes, including indirect effects on aquatic habitats via regulation of erosion and water quality. As soil communities and processes are an important determinant of above-ground communities, ecological restoration and other types of NbS increasingly need to consider below-ground factors that will influence the establishment of semi-natural habitats (Farrell et al., 2020; Young et al., 2005). However, restoration usually focuses on recovering vegetation composition and structure, with the role of soils often forgotten (Farrell et al., 2020), even though degraded soils with compromised ecosystem functions can limit the effectiveness of restoration efforts (Gatica-Saavedra et al., 2023).

Despite the vital role of soils, between 60% and 70% of the soils across the EU are categorized as unhealthy due to unsustainable management practices, losses in soil organic carbon and threats to biodiversity (Borrelli et al., 2017; European Commission, 2023). Therefore, it is important that maintaining soil health and its contribution to ecosystem functions is integrated into the design, implementation and monitoring of NbS and supporting policies (Guerra et al., 2021; Zwetsloot et al., 2022). However, the characteristics of a healthy soil are context-specific, as what constitutes healthy soil in one environmental system may be considered unhealthy in another (Bünemann et al., 2018; Bone et al., 2014). Addressing this, and other challenges, is important for effective soil health monitoring.

4 | SOIL HEALTH MONITORING: CHALLENGES AND OPPORTUNITIES

4.1 | Why we need to monitor soil health

A robust monitoring system is needed to ensure that soil health is maximized alongside the other benefits from NbS. This will allow us to assess progress in restoration efforts (Muñoz-Rojas, 2018), identify the most effective actions for enhancing soil health and provide insights for developing new adaptation strategies in response to future change (Gatica-Saavedra et al., 2023; Guerra et al., 2021). Robust yet streamlined monitoring, reporting and verification (MRV) systems are also essential to ensure policies and practices aimed at improving soil health (including financial incentives) are effectively implemented and are delivering intended outcomes. This could allow policies to be refined based on empirical evidence, ensuring they remain effective. Using soil health monitoring data can help design policies that focus efforts where they are most needed, for example by identifying target areas where soil degradation is occurring (Gutierrez et al., 2024).

More consistent monitoring of soil health could present many opportunities to enhance the effectiveness, scalability and impact of NbS on global environmental and sustainability goals. For example, increased soil carbon sequestration is expected to contribute to enhanced ambition in climate change mitigation, such as through large-scale changes in land use or the application of biochar or other novel soil amendments. However, there remain considerable uncertainties over the efficacy and wider impacts of these major changes to soil management. Therefore, it is important that MRV programmes are put in place to ensure that these provide the anticipated benefits (Lynch et al., 2023). Monitoring can also help to identify and manage any trade-offs that occur between different goals such as food production, flood and erosion protection, carbon storage and biodiversity, ensuring that soil management actions support, rather than frustrate, broader NbS outcomes.

4.2 | Existing assessment tools

Since the 1990s, many tools for assessing and monitoring soil health have emerged (Bünemann et al., 2018). For instance, the Cornell Soil Health Test to assess soil health, soil degradation and increase productivity focused specifically on farmers. Policy-led tools such as the European Soil Monitoring and Assessment Framework focused on providing objective, reliable and comparable information at European level. However, explicit assessment of soil quality considering specific threats, functions and ecosystem services has rarely been conducted, due to a lack of clear interpretation frameworks for the measured indicators. This limits the use of these assessments by land managers and policymakers (Bünemann et al., 2018).

Historically, research on soil health indicators tended to focus predominantly on those relevant to agricultural management, especially the role of soil in food production (Powlson et al., 2011). Only recently have indicators that reflect the wider functions of soils beyond agriculture (e.g. supporting climate resilience, water quality and human health) begun to gain attention (Harris et al., 2023; Zwetsloot et al., 2022). Soil biodiversity and soil biological properties are considered essential metrics for understanding and assessing soil health (Guerra et al., 2021; Lal et al., 2021; Wall et al., 2015; Zwetsloot et al., 2022). However, a review by Bünemann et al. (2018) found that the key metrics used to assess soil were mostly physical and chemical indicators, notably SOC, soil pH, bulk density, available phosphorus and water storage. Biological metrics such as soil respiration and earthworm abundance were mentioned less often, and absent in 40% of the publications and tools reviewed by Bünemann et al. (2018).

In the UK, the UK Centre for Ecology & Hydrology (UKCEH) chose a set of four key indicators to monitor soil health across the UK, including a benchmark for each across different landscape types. These were bulk density, SOC, pH and earthworm abundance (Feeney et al., 2023), hence covering physical, chemical and biological aspects. Similar approaches in the UK include the Soil Health Scorecard (AHDB, n.d.) and Soilmentor (Vidacycle, 2024). These both measure soil organic matter (SOM), pH, earthworms and a visual evaluation of soil structure, plus phosphorus, potassium and magnesium for AHDB and bulk density, nitrogen and the C:N ratio for Soilmentor. While these tools are useful, relying on a limited set of indicators might not capture the full breadth of soil health and its multifunctionality, and may not fully account for the specific conditions or issues pertinent to different regions. Additionally, these indicators are based on measuring the top 15 cm only, and not the full soil profile. A more comprehensive and flexible set of soil health indicators, tailored to the specific contexts and goals of different regions and land uses, would likely be more effective in capturing the complexity of soil health and guide towards a more effective sustainable management of the UK's diverse landscapes.

Despite the variety of approaches available, challenges arise because of differing metrics, sampling protocols and interpretation methods, with some approaches contested (e.g. different methods of measuring soil carbon) and most approaches primarily targeting soil health within the farming context.

4.3 | Moving towards standardized soil assessments

The effectiveness of soil health monitoring can be greatly enhanced by developing a standardized assessment framework (Gatica-Saavedra et al., 2023). Wider application of standardized soil health assessments could provide a consistent basis for evaluating soil conditions, identifying soil degradation and tracking progress across NbS projects in different locations and ecosystems. Standardization can also encourage increased sharing of knowledge and capacity building amongst stakeholders, improving the collective understanding of soil health and management practices (Loveland et al., 2002). This could enable greater practical evaluation of NbS impacts on soil health, facilitating the demonstration of benefits, identification of best practices, adjustment of strategies based on empirical evidence and identification of areas in need of more intensive interventions (Parliament. House of Commons, 2023, Sala et al., 2023; Yakovlev & Evdokimova, 2011).

Despite these opportunities, it is challenging to develop standardized metrics that are applicable across a diversity of soil types and conditions, particularly because thresholds may not be consistent or relevant on a large scale. Furthermore, capturing the interdependence of biological, physical and chemical properties within a limited set of standardized metrics is difficult. In addition, measurement and monitoring techniques can vary in complexity, cost and accuracy, and different stakeholders (e.g. farmers, policymakers, conservationists and researchers) will have different priorities, knowledge levels and interests (Deeks & Rickson, 2023). Given the complexity of soil socio-ecological systems, a 'one-size-fits-all' approach is unlikely to accurately reflect soil health (Harris et al., 2023). Crucially, it is important to consider a dynamic reference state when monitoring soil, which can be a baseline condition that accounts for variability in soil properties due to management practices, ecological states and environmental factors (Adeleke et al., 2024). Instead, a holistic approach based on an understanding of soil functions may be more appropriate, selecting metrics that reflect the capacity of soil to provide a range of essential services (Zwetsloot et al., 2022).

4.4 | How to select suitable soil health indicators for monitoring

The first step to developing a robust monitoring system is to identify appropriate soil health indicators: measurable attributes or properties of soil that serve as proxies for its condition, quality and ability to function effectively within natural or managed ecosystem boundaries. Indicators are 'purpose-dependent', meaning that the selection of specific indicators is influenced by the objectives or goals of the evaluation (Harris et al., 2023). Selecting appropriate indicators ensures that the assessment accurately reflects the true state of soil health, providing a solid foundation for making informed decisions about land management, agricultural practices, conservation efforts and supporting policies (Deeks & Rickson, 2023). Desirable attributes of a soil health indicator include its relevance to ecosystem functions and services (Bünemann et al., 2018; Lehmann et al., 2020); sensitivity to change without overly reflecting short-term oscillations; interpretability and replicability (Stott, 2019); practicality of data collection; cost-effectiveness; short turnaround time for analysis; and usefulness for informing soil/land management (Lehmann et al., 2020). However, it is important to acknowledge that indicator selection and interpretation are highly scale-dependent and influenced by the availability of resources (monetary and human) at a local level to undertake soil health assessment (Lobry de Bruyn & Andrews, 2016). This often means that farmers and land managers may need to rely on indicators that are accessible and practical, even if they are not ideal in all respects.

A useful approach for selecting soil health indicators is the application of logical sieve methods. These provide a structured framework for selecting soil health indicators, allowing for the ranking and prioritization of candidate indicators based on a balance of scientific validity and technical feasibility. This approach, as demonstrated by Ritz et al. (2009) and Stone et al. (2016), systematically scores potential indicators against a range of criteria, such as ecological relevance, methodological robustness and practical applicability. It involves input from experts and stakeholders, who weigh different factors such as the sensitivity of an indicator to environmental changes, its cost-effectiveness and ease of implementation. For example, biological indicators, such as microbial diversity, enzyme activity assays and functional gene profiling, were ranked highly in both frameworks because of their ability to reflect ecological functions while being adaptable to various soil types and conditions. These indicators can complement traditional physical and chemical metrics, providing a more holistic view of soil health.

It can also be useful for indicators to include or suggest defined threshold values (Rinot et al., 2019): 'values above or below which a significant shift or rapid adverse change takes place' (Van Lynden et al., 2004). The use of these thresholds should be carefully considered, as thresholds can be context specific and may not universally apply across different soil types, climates or management practices, making it crucial to interpret them within the appropriate context. Collectively, the metrics should represent physical, chemical and biological components of soil health. It is important to recognize that currently available data underrepresents biological and physical properties of the soil, with most focus on the chemical properties. These practices may fail to capture the full complexity of the soil profile or the dynamic interaction between soil properties. These relationships can be synergistic or counterproductive, and a more comprehensive approach to soil health assessment should seek to address these gaps. Additionally, it is important to acknowledge that not all metrics will comprehensively capture these aspects at every scale. The challenge lies in selecting a balanced set of indicators that collectively represent the key dimensions of soil health while being applicable across different contexts and scales.

4.5 | Emerging technologies for soil health monitoring

Traditional soil assessments require time-consuming field sampling and laboratory analysis. The integration of new technologies into MRV systems presents an opportunity for enhancing the implementation and scalability of NbS. These can be combined by using the more accurate but more expensive laboratory methods to validate key in-field indicators when needed, ensuring that robust data are collected cost-effectively. For instance, proximal soil sensing (use of sensors close to or in contact with the soil to quickly measure various soil properties directly in the field) can offer rapid, large-scale data collection capabilities while minimizing ecosystem disruption and reducing reliance on labour-intensive manual methods (Lardo et al., 2012; Schirrmann et al., 2016). Similarly, Internet-of-Things-based smart soil sensors can provide real-time insights into soil health (e.g. soil nutrient levels, moisture, pH and electrical conductivity) (Pyingkodi et al., 2022; Ramson et al., 2021; Soetedjo & Hendriarianti, 2023).

Critical evaluation is needed to ensure that sensors offer consistent and replicable data across different soil types and environmental conditions, and, as for traditional methods, their data should be validated through ground-truthing to ensure accuracy. It is important that sensors are used in conjunction with an understanding of the soil type and its specific characteristics, ensuring that the data can be compared with the expected healthy range for that soil type. Sensors should be evaluated on their sensitivity to both short-term variations and long-term changes in soil properties. For example, the assessment should aim to distinguish the inherent health of the soil from transient management impacts such as elevated nutrient levels from synthetic fertilizer inputs.

Environmental DNA (eDNA) analysis can allow for rapid identification of all species present in an ecosystem, facilitating soil biodiversity assessment (Rota et al., 2020). It offers a streamlined approach for establishing diversity benchmarks and tracking changes in communities because of management actions (Kestel et al., 2022). This approach is particularly useful for establishing biodiversity baselines in areas where none exist and for monitoring changes over time at various scales, from small-scale projects to larger landscape-level assessments (Kestel et al., 2022). However, incomplete databases and biases in assay design can hinder accurate taxonomic identification, necessitating rigorous testing and validation of eDNA methods (Kestel et al., 2022), while the presence of non-selective DNA signals can lead to false negatives, complicating species detection and biodiversity assessments (Yun et al., 2023).

Ecoacoustics is another emerging technology that is gaining recognition as a method for detecting and monitoring soil biodiversity. It has been utilized to monitor soil biodiversity across various forest restoration environments, such as temperate forests in the UK (Robinson et al., 2023) and grassy woodlands in Australia (Robinson, Taylor, et al., 2024). The use of soil ecoacoustics presents several challenges, as it is important to consider the impact of environmental factors such as heavy rain, soil saturation, compaction, root networks and soil texture on sound propagation in terms of wave speed, amplitude and frequency (Robinson, Taylor, Fickling, Sun, & Breed, 2024; Robinson et al., 2024).

In summary, while these emerging technologies can offer substantial benefits for collection speed and provide a deeper understanding that supports more efficient environmental management, they also introduce other notable challenges. The cost of implementing these technologies can be high as initial investments can be required for purchasing and maintaining equipment. Furthermore, specialized skills are needed to operate the equipment, interpret the data and troubleshoot issues. In many cases, training or hiring experts is necessary, which adds to the cost and complexity (Silvero et al., 2023). These challenges can limit the accessibility and scalability of such technologies, particularly in small-scale or resource-limited settings. Therefore, while these tools present significant potential for advancing soil health monitoring, cost-effectiveness and capacity building must be carefully considered to ensure successful integration.

5 | INTEGRATING SOIL HEALTH ASSESSMENTS INTO NbS MONITORING FRAMEWORKS

5.1 | The need for an integrated approach combining soil science and ecology

NbS monitoring frameworks need to apply an integrated, interdisciplinary approach which includes soil health and other indicators of biodiversity and ecosystem health, alongside ecosystem services and socio-economic outcomes. Merging insights from soil science and ecology can support more comprehensive ecosystem management: soil science elucidates the physical, chemical and biological aspects of soil health (Stewart et al., 2018), while ecology provides an understanding of the interactions within ecosystems, including biodiversity and ecosystem services (Kremen, 2005). This enables design and implementation of NbS that optimize both above-ground and below-ground biodiversity and ecosystem services. For example, Kardol and Wardle (2010) proposed a conceptual framework for considering above- and below-ground linkages in restoration ecology, recognizing that actions taken at one ecological level have cascading effects on other levels. Similarly, in response to the lack of comprehensive environmental monitoring programmes, Andrés et al. (2021) presented a set of soil and plant indicators designed to monitor NbS for disaster risk reduction focused on slope stabilization to reduce landslides. By supporting sustainable practices that benefit both soil ecosystems and overall environmental health, integrated monitoring can aid in delivering the SDGs (Bouma et al., 2019; Lal et al., 2021).

Integrating a range of monitoring techniques which encompass soil and above-ground biodiversity alongside socio-economic outcomes can present a cohesive narrative on ecosystem health and has the potential to provide a greater understanding of NbS to a wider variety of stakeholders. For example, research on global grasslands has shown that both above- and below-ground biodiversity—such as plant and microbial diversity—independently influence different aspects of ecosystem functionality, contributing to nutrient cycling, soil health and plant productivity (Martins et al., 2024). This suggests that integrating diverse monitoring techniques can offer a holistic picture of ecosystem health, encompassing both ecological and human dimensions.

Several existing projects highlight the importance of soil monitoring in restoring ecosystems. For example, the Moldova Soil Conservation Project used reforestation to combat soil erosion and improve soil stability, showcasing the potential benefits of monitoring soil health as part of NbS projects (NbSI, n.d.). Similarly, the Mountain Ecosystem-based Adaptation Project in Nepal demonstrated improvements in soil productivity and resilience through organic soil nutrient management and restoration efforts, contributing to both ecosystem and socio-economic outcomes (NbSI, n.d.). A global review highlighted the importance of soil monitoring during rehabilitation of mining sites, where the original soil has been completely removed (Martins et al., 2020). These case studies underline the need for further exploration and consistent soil monitoring protocols to assess cumulative impacts and improve the effectiveness of NbS projects in different contexts. However, they also point out gaps, such as the need for robust long-term monitoring. The development of further case studies focused specifically on soil monitoring in NbS is essential to validate and substantiate the approach of integrating soil health alongside biodiversity and socio-economic outcomes.

From a practical perspective, conducting above and below-ground sampling simultaneously can optimize time and resources. Just as in landscape ecology, where spatial and temporal factors are crucial for understanding ecological patterns, soil health monitoring must account for the complexity and variability of soil systems across different landscapes and consider site-specific conditions (Stockdale et al., 2019). Therefore, the efficiency and cost-effectiveness of monitoring initiatives can be improved by establishing a denser network of monitoring sites and including a broader variety of taxa and ecosystems (Breeze et al., 2023). Moreover, developing and utilizing shared databases for both soil and ecological data not only streamlines monitoring activities but also provides a more comprehensive insight into the effects of land management practices on ecosystem health. By implementing robust monitoring frameworks that include both soil health and above-ground biodiversity, we can ensure that efforts to improve one do not adversely affect the other, something that is lacking in many EU policies (Vrebos et al., 2017). This integrated approach helps in crafting evidence-based policies and informs targeted conservation actions (Guan et al., 2023). For example, Guerra et al. (2021) showed how soil biodiversity indicators can be integrated into monitoring frameworks to inform policies on nature conservation, agriculture, forestry and climate, such as by identifying conservation areas to protect soil biodiversity and its ecosystem functions.

As well as integrating soil biodiversity indicators into monitoring frameworks, it is important to develop more nuanced approaches that consider the complex and intricate relationships and synergies between soil health and the specific needs of soil biota (Lobry De Bruyn, 1999). These relationships are often overlooked, with the simplistic assumption that if soil is managed well, the biota will take care of themselves. For example, changes in soil biota due to agricultural practices often go unstudied, particularly because of the lack of dynamic reference sites that could track these shifts over time. This data gap makes it challenging to establish causality and fully understand the long-term impacts of soil management on biota.

In the UK, valuable data and significant insights into the integration of above and below-ground analyses are provided by the long-term UK Countryside Survey, revealing the critical interdependencies between soil characteristics such as pH and nitrogen levels, plant diversity and ecosystem health (Reynolds et al., 2013). In addition, the new England Ecosystem Survey (EES) will measure 24 soil indicators, covering physical, chemical and biological properties of soil, alongside data on vegetation, waterbodies and landscape change. With thousands of 1 km^2 grid squares in different habitats sampled every 5 years, this survey will support England's 25-Year Environment Plan by informing the new Soil Health Metric and contributing to a new baseline map of soil health (Natural England, 2024).

Integrated assessments require a range of expertise, including soil science, ecology, hydrology and socio-economic aspects, depending on the context of each NbS project. Agronomists and environmental scientists may be best suited to handle technical soil and water quality monitoring in agricultural or ecosystem restoration projects, while urban planners and environmental engineers could monitor green infrastructure in cities. Community-based organizations, citizens, researchers, non-profit organizations and some government agencies, like municipal park districts or water authorities, can also support sampling and monitoring, especially in urban projects such as stormwater control (Kumar et al., 2021; Obrien et al., 2023). Advisors, extension services or local conservation organizations may also play a key role in providing guidance and facilitating the process (Matthews et al., 2022). The involvement of land managers, whether farmers or urban planners, may depend on time constraints, necessitating the provision of accessible, user-friendly tools and technologies, as well as external support, to ensure that robust above- and below-ground sampling is effectively conducted across diverse contexts.

5.2 | The role of stakeholder engagement in NbS implementation and monitoring

NbS must be delivered in collaboration with local stakeholders, leveraging local knowledge to ensure relevance and effectiveness (IUCN, 2020). Engaging a wide array of stakeholders can lead to more effective resource mobilization and help ensure that NbS projects are resilient, sustainable and capable of achieving their intended goals (Cumming et al., 2022; Seddon et al., 2021). Involving community members in NbS planning, implementation and monitoring can develop a sense of ownership that can lead to a greater commitment to the success and maintenance of NbS projects (Gómez Martín et al., 2020). Frantzeskaki (2019) provides several case studies with positive outcomes that contributed to urban resilience, in which NbS involved citizens in the planning and realization phases. Engaging governmental bodies, NGOs and the private sector can align NbS initiatives with existing policies and sources of finance and help facilitate the integration of NbS into broader environmental and economic policies. Ultimately, inclusive engagement can foster a collaborative environment, where diverse stakeholders can offer different perspectives and solutions that enhance the design and implementation of NbS, ensuring they meet both local and national goals (Seddon et al., 2021). Moreover, integrated monitoring also facilitates the evaluation of policy outcomes over time and encourages cross-sectoral collaboration, thereby enhancing the effectiveness of NbS (Albert et al., 2021).

Local communities often possess invaluable knowledge and expertise that can enhance the design of NbS by aligning them more closely with the specific ecological and social context of the area. This is particularly important for soil assessment, where farmers and other land managers typically have a detailed knowledge of the fine scale variation in soil properties on their land, such as areas that are poorly drained, easily eroded or infertile (Barrios & Trejo, 2003; Lobry De Bruyn et al., 2017). Developing clear and flexible monitoring frameworks that meet the needs of a range of stakeholders with different and asymmetrical skills and resources can support the integration of local knowledge, helping to address complex environmental challenges through informed, adaptive strategies (McKay & Johnson, 2017). In order to effectively integrate local knowledge and address complex environmental challenges, it is essential that these frameworks are also co-designed with the stakeholders involved. For example, community-based environmental monitoring (CBEM) programmes are often co-developed with local communities to ensure that monitoring protocols reflect local priorities and capabilities, facilitating the integration of traditional knowledge and scientific methods (McKay & Johnson, 2017).

5.3 | The biodiversity and soil health metrics tool

In response to the need for an integrated soil and ecology monitoring framework to support the scaling-up of high-quality NbS, a Biodiversity and Soil Health Metrics Tool has been developed in the UK (NbS Knowledge Hub, 2024; Warner et al., in review). This interactive tool aims to provide a structured framework to help practitioners select the most suitable metrics for assessing above-ground biodiversity and soil health outcomes in NbS projects from a carefully selected list (Figure 2). The flexible approach allows users to tailor monitoring strategies to the specific project needs and local context. It categorizes metrics into two tiers and future metrics, based on cost and expertise requirements, ranging from highly feasible to the more aspirational future metrics, allowing users to select metrics suited to their skills and resources (Warner et al., 2024).

6 | POLICY OPPORTUNITIES FOR INTEGRATING SOIL HEALTH IN NbS DEPLOYMENT AND MONITORING

Integrating soil health within wider environmental health policies and targets to guide sustainable development is

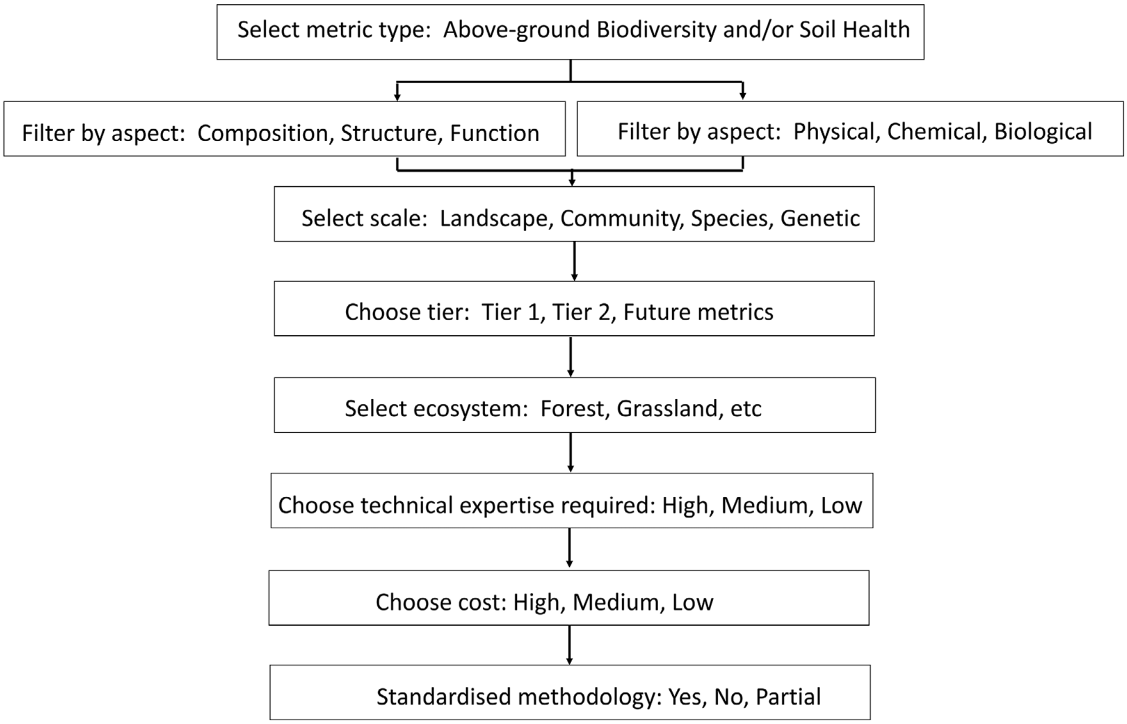

FIGURE 2 Overview of the structure of the Biodiversity and Soil Health Metrics Tool developed to help practitioners in the design and monitoring of NbS as part of the NbS Knowledge Hub, 2024.

gaining momentum globally (Guan et al., 2023). In the UK, for example, several policies have recently been put in place to support nature and soils, reflecting a growing awareness of their importance in environmental sustainability and agriculture. These include the 25-Year Environment Plan in England, which aims for sustainable soil management on all agricultural land by 2030, by addressing soil degradation and improving soil health (HM Government, 2018). However, financial constraints emerge as a significant challenge (Vanino et al., 2023), with the required investment for sustainable soil management and NbS often surpassing budget allocations and financial incentives available to landowners and farmers. This gap in funding can deter the adoption of best practices and innovative solutions necessary for soil health improvement and ecosystem restoration (Duffaut et al., 2022; Thompson et al., 2023).

To effectively integrate soil health into NbS and encourage sustainable practices, supportive policy frameworks and incentives are needed. These not only align economic interests with environmental goals but also provide regulatory support, guidance and funding mechanisms that could enable long-term systemic change. Payment for Ecosystem Services (PES) programmes are a key mechanism for compensating landowners for maintaining or enhancing ecosystem services that benefit society, but which do not provide direct income (Bulte et al., 2008; LaRocco & Deal, 2011). Agri-environment schemes are a common type of PES. These can provide government subsidies to farmers who invest in soil health, aiming to make this financially viable by offsetting the initial costs of a transition towards more sustainable practices (Akkaya et al., 2019; Isabella, 2023). In England, for example, the Environmental Land Management (ELM) schemes provide subsidies to incentivize farmers to adopt sustainable farming practices, including by improving soil health, and create habitat for nature recovery. One of these schemes is the Sustainable Farming Incentive (SFI), which aims to reward farmers for the public goods they provide such as healthy soils, clean air and water, carbon storage and rich habitats (DEFRA, 2024).

Similarly, monetizing carbon credits for soil carbon sequestration can provide a direct financial incentive for landowners and farmers to adopt practices that improve soil health and enhance carbon storage, such as reforestation, cover cropping and reduced tillage. However, it is important to note that if landowners or farmers need to achieve carbon neutrality themselves, they may need to retain the carbon credits for their own offsets, which would limit their ability to sell or trade these credits and therefore reduce potential income (Badgery et al., 2020; de Gruijter et al., 2018). Direct sampling of soils is essential to confirm and reward improvements in soil health and refine management methods to be more effective (Smith et al., 2020; Vrebos et al., 2017). A surveying scheme should be included to establish a baseline from which to confirm increases in soil carbon and improvements in soil health, incorporating GHG emissions alongside soil carbon sequestration. This can ensure a more holistic approach to awarding carbon credits. Although soil carbon markets are still developing in the UK, there is growing interest in monetizing carbon credits for soil carbon sequestration through initiatives like the UK Farm Soil Carbon Code (SSA, 2024).

Policy can extend beyond implementation to also encourage better monitoring. For instance, the ELM SFI scheme includes payment for carrying out a basic soil survey, as well as for practices such as reduced tillage or addition of organic matter to soils. This could facilitate the standardization and comparability of soil data, by making soil assessments and testing techniques standard across the UK, facilitating more effective evaluation of land management practices (Parliament, House of Commons, UK, 2023).

Incentive schemes need to be complemented by the enforcement of policies and regulations that protect soils from degradation and limit harmful practices, ensuring that minimum environmental standards are met and aiding the conservation of soil health (Louwagie et al., 2010; Vrebos et al., 2017). However, regulatory measures alone are not enough, and it is equally important to collaboratively support farmers and land managers by providing them with the necessary knowledge and skills needed to implement effective soil health practices. This could involve extension services, training programmes, and access to best practices and innovation in soil health management. Investing in research and development focused on soil health, sustainable agricultural practices and NbS can lead to new technologies, methods and approaches that further enhance policy and practical outcomes (Honeycutt et al., 2020).

7 | RECOMMENDATIONS

Future avenues for research and development include the development of innovative and cost-effective soil monitoring technologies; long-term impact studies to assess the sustainability of NbS interventions (Cohen-Shacham et al., 2019; Dick et al., 2020); the role of the soil microbiome in ecosystem health (Schloter et al., 2018); cost–benefit assessment of soil health practices (Tepes et al., 2021); creation of soil health databases which support evidence-based policymaking (Jian et al., 2020); and standardization of key soil health indicators. The Biodiversity and Soil Health Metrics Tool for the UK (Warner et al., 2024), with its structured framework for selecting appropriate monitoring metrics for soil and ecological health, could serve as a basis for others to build upon, potentially enhancing the effectiveness of ecological monitoring.

8 | CONCLUSION

Soil health is foundational to the success and sustainability of NbS. Healthy soils deliver multiple vital functions, such as enhancing biodiversity, storing and sequestering carbon, regulating water flows and bolstering agricultural productivity, as well as underpinning resilience to environmental change.

Integrating soil health into NbS design, implementation and monitoring can amplify these benefits, contributing significantly to global sustainability goals such as climate change mitigation and adaptation. This requires a holistic approach. Policymakers need to design effective incentives to encourage sustainable soil management practices and regulations to prevent soil degradation. Researchers and practitioners need to collaborate across disciplines to design NbS that fully consider interactions between soil health and above-ground ecology. Investing in new monitoring technologies and standardizing soil health metrics should improve consistency in tracking NbS performance and build the evidence base needed to identify best practices. Capacity building through training and resources for stakeholders, coupled with active public and stakeholder engagement, is critical for implementing effective NbS. Together, these strategies could not only enhance soil health integration into NbS but also strengthen global climate resilience and sustainability efforts.

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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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