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BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

REVIEW

Integrated above- and below-ground ecological monitoring for nature-based solutions

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Abstract

1. As the development of nature-based solutions (NbS) increases globally, it is important to ensure that projects meet the objective of delivering benefits for biodiversity, alongside tackling societal challenges. However, this is challenging because most NbS projects do not directly monitor ecological outcomes, and those that do often focus on a limited set of metrics.
2. We identify the most informative and feasible above- and below-ground ecological metrics for monitoring the ecological outcomes of NbS. We identify possible biodiversity and soil health metrics using a structured non-systematic literature review, and rank these using a scoring system to assess their informativeness and feasibility for monitoring.
3. Metrics are categorised into compositional, structural, and functional aspects of biodiversity, and biological, physical and chemical aspects of soil health. We group biodiversity and soil health metrics into Tier 1 (the most informative and feasible metrics), Tier 2 (informative metrics with some limitations in scope or feasibility) and Future metrics (highly informative metrics which are currently less feasible to monitor). Tier 1 metrics collectively address multiple aspects of biodiversity and soil health and are the highest priority for NbS project assessments. For biodiversity, 9 Tier 1, 6 Tier 2 and 15 Future metrics were identified, and for soil health there are 11 Tier 1, 6 Tier 2 and 5 Future metrics.
4. We identify existing standardised methodologies, threshold and reference values for monitoring these metrics, although in many cases, these are not available.
5. *Solution*. Our study provides practitioners with a framework for selecting optimum metrics for assessing above- and below-ground ecological outcomes of NbS relevant to the location in which they are being implemented. We summarise the relevance of each metric to biodiversity or soil health and provide standardised methodologies for collecting data to support ecological monitoring protocols for NbS projects. The information on each metric is freely available as a searchable online database designed for UK practitioners, but with wider applicability.

KEYWORDS
biodiversity, ecological monitoring, nature-based solutions, soil health

1 | THE NEED TO MONITOR THE ECOLOGICAL OUTCOMES OF NbS

Nature-based solutions (NbS) involve working with and enhancing nature to tackle societal challenges, with biodiversity both underpinning their benefits and directly benefiting from the interventions (Seddon et al., 2020, 2021). Global uptake of NbS is accelerating as their role in tackling issues from climate change to food security gains recognition (Chausson et al., 2020; Donatti et al., 2022; Seddon et al., 2019).

Nature supports ecosystem services through multiple pathways, from overall habitat structure to the presence of specific species or functional groups (Smith et al., 2017). These pathways are linked to biotic and abiotic attributes representing above- and below-ground components of ecosystems at multiple scales, such as species richness, landscape diversity or geology (Smith et al., 2017). Interactions between these components influence ecosystem function and the delivery of ecosystem services (Chomel et al., 2022). Soil health and quality are therefore increasingly integrated into ecological restoration plans, as soil biota and processes shape ecosystem health and the establishment of above-ground communities (Farrell et al., 2020; Young et al., 2005). Soil communities drive key ecosystem services, such as erosion control, hydrological functions and nutrient exchange (Barrios, 2007; Bhaduri et al., 2022; Farrell et al., 2020). Maintaining soil health and biodiversity is essential for ecosystem stability and resilience against disturbances such as climate change (Seddon et al., 2019).

Monitoring of NbS needs to cover societal benefits (e.g. flood protection, carbon storage), socio-economic outcomes (e.g. employment, community engagement) and ecological benefits. Yet despite recognising that biodiversity and soil health underpin resilient NbS with multiple benefits, biodiversity benefits are often implicitly assumed to arise from NbS projects rather than being explicitly planned and monitored. A review of 386 studies on NbS for climate change adaptation found only 34% reported ecological outcomes (Chausson et al., 2020), and these often used a limited set of metrics (Key et al., 2022). Empirical monitoring of ecological outcomes of NbS allows objective assessment of success, bridging science and policy (Lovett et al., 2007; Mallette et al., 2022). More effective monitoring strategies are therefore needed to track biodiversity and soil health changes, confirm positive outcomes, highlight trade-offs and assess management efficacy (Farrell et al., 2020).

A recent initiative on scaling up high-integrity NbS in the United Kingdom (Agile Initiative, n.d.), identified the need to strengthen the evidence base on 'what works' through more effective, consistent monitoring, while considering time and resource limits. The IUCN Global Standard for NbS also calls for monitoring of management targets, but provides only high-level guidance (IUCN, 2020). A European Commission Handbook on evaluating NbS provides extensive information on developing monitoring protocols and an Appendix detailing methods, but lacks practical guidance on metric prioritisation, clear data collection protocols and detailed biodiversity assessment advice (Dumitru & Wendling, 2021). With numerous possible indicators to choose from, practitioners need guidance on selecting biodiversity and soil health metrics aligned with project and place-based objectives (Bhaduri et al., 2022; Bünemann et al., 2018; Knight et al., 2020; Noss, 1990).

To address this, we developed a framework for selecting biodiversity and soil health metrics for NbS monitoring by:

- Reviewing literature to identify a range of possible biodiversity and soil health metrics across categories at multiple scales.
- Presenting a strategy for prioritising biodiversity and soil health metrics based on informativeness and feasibility.
- Identifying existing protocols, using the United Kingdom as a case study, for monitoring metrics and highlighting gaps where standardised methodologies are required.
- Providing a case study demonstrating the practical implementation of the framework.
- Highlighting technological innovations to simplify monitoring for practitioners.

This resulted in a searchable database of metrics and their characteristics, aimed at UK practitioners but with wider applicability, available on the NbS Knowledge Hub developed through the Agile Initiative (https://nbshub.naturebasedsolutionsinitiative.org/monitoring-outcomes/) (Agile Initiative, 2025).

2 | A CONCEPTUAL FRAMEWORK FOR BIODIVERSITY AND SOIL HEALTH METRICS

Effective monitoring programmes should use accepted, ideally standardised, methods to ensure consistent, cost-effective collection of high-quality data (Lovett et al., 2007; Pocock et al., 2015). Data use and outputs should be considered throughout planning, with clearly defined, future-relevant aims (Lovett et al., 2007; Pocock et al., 2015). Conservation activities often include monitoring, but without a quantitative, scientific approach, impact may be limited (Legg & Nagy, 2006). Practicality and cost-effectiveness are also crucial considerations for practitioners (Cosović et al., 2020; Czúcz et al., 2021; Heink & Kowarik, 2010; Wurtzebach & Schultz, 2016).

Biodiversity and soil health monitoring requires selecting widely representative indicators, that is, measurable characteristics (Niemi & McDonald, 2004). To comprehensively track ecological change, multiple complementary metrics should be assessed

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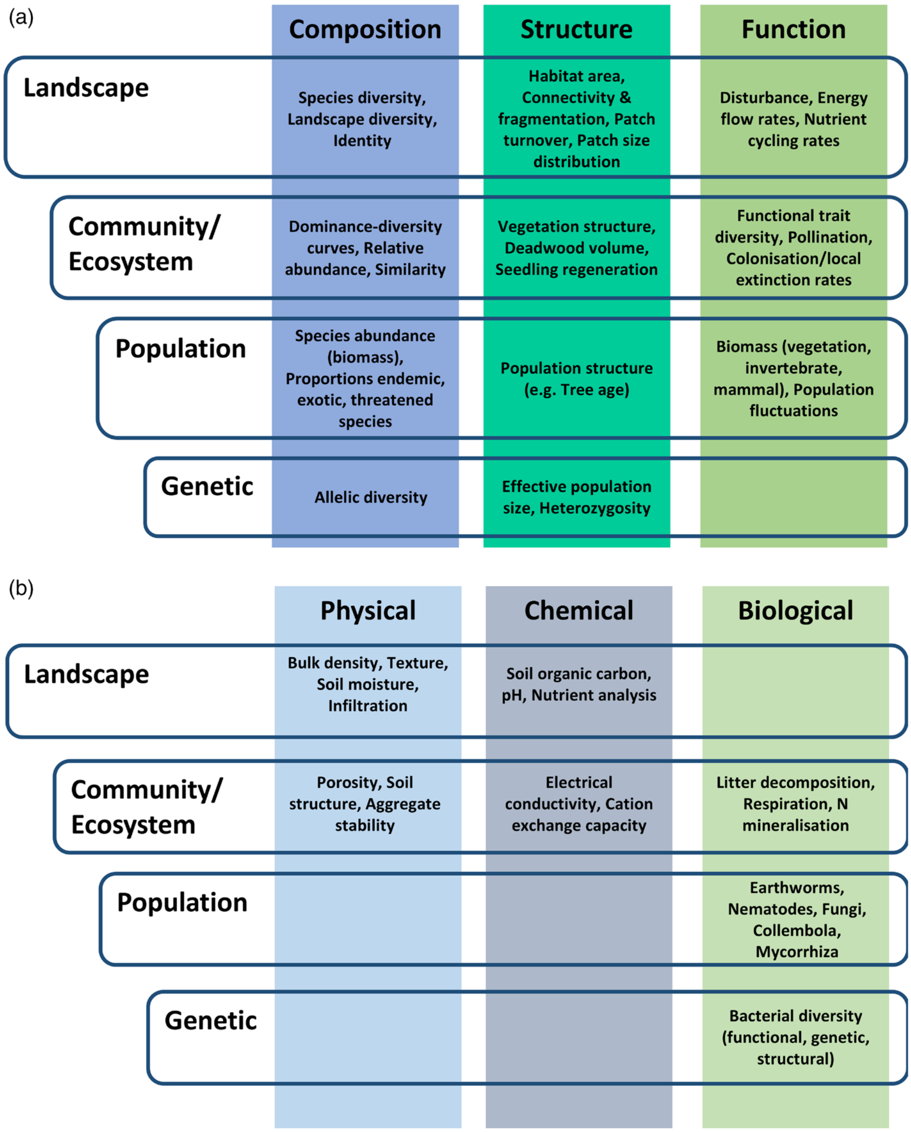

FIGURE 1 Metrics representing the primary attributes of (a) biodiversity (composition, structure and function), adapted from Noss (1990), and (b) soil health (physical, chemical and biological) at multiple scales (landscape, community/ecosystem, population and genetic). Some metrics apply to multiple axes and scales (see Tables S1 and S2).

(Czúcz et al., 2021; Knight et al., 2020; Niemi & McDonald, 2004). Yet due to the complexity and multidimensionality of biodiversity and soil health, monitoring often focuses on a limited set of metrics (Bünemann et al., 2018; Key et al., 2022). One solution is to classify biodiversity and soil health into distinct components, and aim to assess metrics relevant to each group (Niemi & McDonald, 2004). Noss's biodiversity hierarchy identifies three components: structure (physical organisation e.g. habitat complexity), composition (identity and variety of elements e.g. species diversity) and function (processes within a system e.g. nutrient cycling; Figure 1a), further categorised by scale (gene to landscape; Niemi & McDonald, 2004; Noss, 1990). Similarly, soil health can be subdivided into physical, chemical and biological characteristics (Figure 1b; Guo, 2021; Jian et al., 2020; Stewart et al., 2018).

The Noss Framework provides a comprehensive systematic approach that has been used to underpin monitoring, including biodiversity mitigation and ecological integrity assessments (Andreasen et al., 2001; Knight et al., 2020). Yet most programmes still equate biodiversity to species richness, rarely assessing functional and structural aspects (Feld et al., 2009) and thus providing only partial biodiversity information (Hines & Pereira, 2021; Lyashevska & Farnsworth, 2012). An ideal monitoring approach would include metrics across composition, structure and function at multiple scales (genetic, population, ecosystem and landscape; Knight et al., 2020).

Soil health is similarly complex; soils are heterogeneous, varying by environmental context and land-use history, which influence their functions (Bünemann et al., 2018). Soil health indicators fall into three categories: biological (properties relating to living organisms e.g. fungal diversity), physical (soil structural properties e.g. bulk density) and chemical (properties linked to soil chemical composition e.g. pH), which interact to maintain soil functions (Guo, 2021). Physical and chemical properties are typically easier to measure, while biological indicators require further research and development (Guo, 2021). Soil monitoring programmes vary in coverage across these categories, often assessing a limited set of indicators (Bünemann et al., 2018; Harris et al., 2023; Loveland & Thompson, 2002). Like biodiversity assessment, effective soil health monitoring should incorporate diverse indicators for fuller representation (Guo, 2021).

The comprehensive multi-metric biodiversity and soil health assessment approach outlined here aligns with assessing ecological integrity (Andreasen et al., 2001; Carignan & Villard, 2002; Karr et al., 2022), that is, an ecosystem's ability to support a balanced, adapted community, with composition, diversity and functional organisation comparable to natural habitat (Karr & Dudley, 1981).

3 | METRIC FRAMEWORK DESIGN AND PRIORITISATION

The compositional, structural and functional axes of biodiversity (Figure 1a) and the physical, chemical and biological axes of soil health (Figure 1b) provide a framework for identifying indicators to assess NbS ecological outcomes. An initial list of biodiversity metrics was drawn from Noss's categories. We then conducted a structured non-systematic review of academic and grey literature, using keyword searches to identify soil health and further biodiversity metrics across axes and scales (see Supporting Information: Methods for full details). We only considered metrics with a clear link to biodiversity or soil health. Although this approach did not review all literature (Romanelli et al., 2021), structuring our review around established biodiversity and soil health monitoring concepts ensures a well-evidenced framing of biodiversity and soil health monitoring.

For each metric, we extracted information on its informativeness and monitoring feasibility (Table 1). Informativeness reflects a metric's value in assessing biodiversity and soil health change; higher scoring metrics have strong evidence of their link to biodiversity or soil health, are widely applicable, are relevant to ecosystem functions/services and respond sensitively to ecosystem management. Feasibility captures practical considerations; higher scoring metrics have simpler data collection, requiring lower technical expertise and costing less, and have robust, standardised methodologies. Metrics were scored on a three-point scale for each criterion (Table 1) to determine their relative value and group them into three categories: Tier 1, Tier 2 and Future (Figure 2) (full details in Supporting Information: Methods, including a full list of all metrics considered).

Tier 1 metrics have the highest informativeness scores and meet a minimum feasibility threshold. Collectively, they provide comprehensive coverage of all biodiversity and soil health axes across multiple scales (Tables S1 and S2). Tier 2 metrics also meet the feasibility threshold and are useful and informative but score less than Tier 1, or are only relevant to specific ecosystem or soil types. Future metrics are highly informative but not yet feasible for regular monitoring. We also collated information on technological innovations that could simplify or accelerate future data collection. Future metrics may transition into Tier 1 as technological advancements simplify monitoring or reduce costs, or as data collection guidance improves.

4 | EXPLORING THE PRIORITY METRICS IDENTIFIED

The highest-ranked compositional biodiversity metrics include species and functional diversity, along with less familiar metrics that link composition to function: dominance-diversity curves, identity, relative abundance and similarity (Table S1). Dominance-diversity curves track shifts in dominant and rare species affecting ecosystem function (Hillebrand et al., 2018). Identity and functional trait diversity capture traits influencing key ecological processes and ecosystem services, offering both diversity and functional insights (Buckland et al., 2005; Hillebrand et al., 2018). Top structural biodiversity metrics include habitat area, landscape diversity and vegetation structure. Habitat area is simple to measure and strongly determines biodiversity. Combined with landscape diversity, it serves as a proxy measure for a landscape's capacity to support different species groups at various scales (Dangerfield et al., 2003; Deane et al., 2020; Maskell et al., 2019; Morelli et al., 2013). The ease of monitoring vegetation structure varies by habitat type; most simply involving categorising variation in tree/shrub height or diameter within a woodland, while in grassland, point-intercept and vegetation height variation methods can be used (Table S3).

TABLE 1 Scoring criteria for biodiversity and soil health metrics.

Informativeness	Feasibility
Relevance: How strong is the evidence that the metric is directly or indirectly relevant to biodiversity/soil health?	*Sample collection*: How straightforward is sample collection and analysis?
Information rich: How many metrics can be calculated from one data collection method? Can the metric be used as a surrogate for other metrics?	*Cost*: How expensive is data collection and analysis?
Sensitivity: How sensitive is the metric to management changes?	*Technical*: How much technical expertise or equipment is needed?
Functions/services: Are there clear links between the metric and ecosystem functions and derived services?	*Methodology*: Is there an existing standardised methodology available?
Applicability: Can the metric be applied across habitat types?	*Compatibility*: Is the methodology robust and repeatable?
Literature: How widely is the metric considered in the academic literature?	*Interpretation*: How easy are results to interpret?

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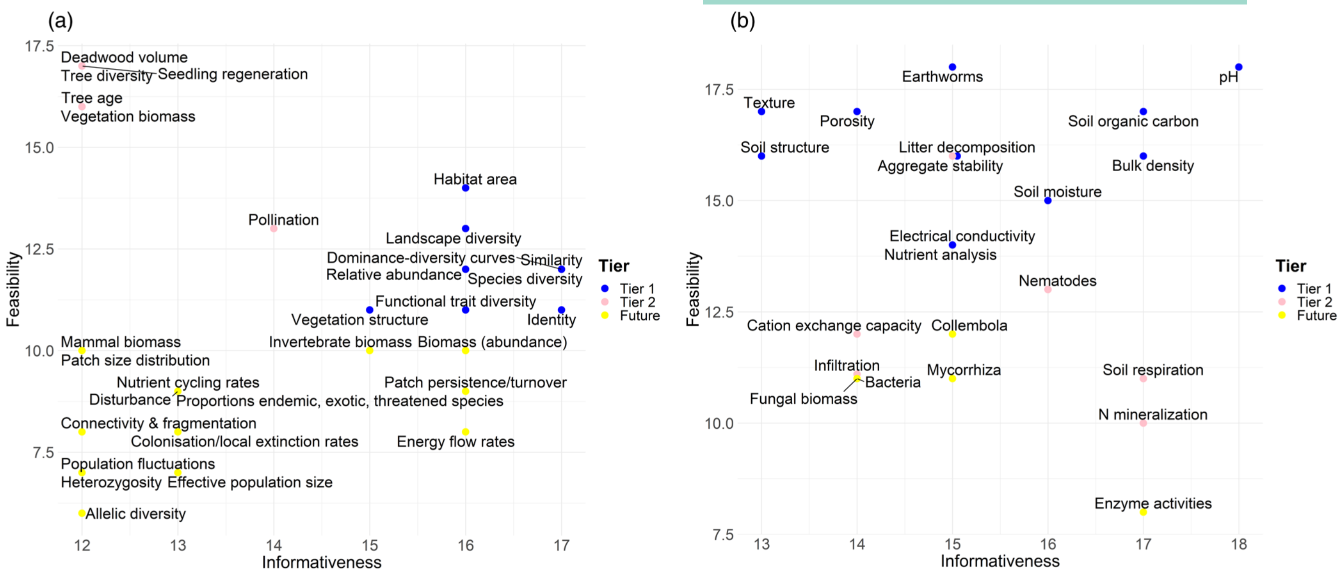

FIGURE 2 (a) Biodiversity and (b) soil health metric scores plotted on the axes of informativeness and feasibility.

Tier 1 physical soil health metrics include bulk density, texture, soil moisture, porosity and soil structure (Table S2). Bulk density, texture and porosity provide information on soil structure and compaction, and determine interactions with air and water (Merrington et al., 2006; Cardoso et al., 2013; Schoenholtz et al., 2000). Bulk density is also needed to convert percentage nutrient or carbon values into volumetric measures. Top-ranked chemical soil health metrics include soil carbon, pH, nutrient analysis and electrical conductivity. Soil carbon affects nutrient storage, water retention, aggregate stability and microbial activity (Cardoso et al., 2013). Nutrient content and type support the soil biotic community, driving nutrient cycling and decomposition (Merrington et al., 2006). Earthworm abundance and litter decomposition are the most accessible soil biological metrics. Earthworms serve as proxies for the broader soil community, physical structure and water dynamics (Griffiths et al., 2016; Pulleman et al., 2012). Earthworms are absent from acidic and/or waterlogged soils; however, they remain a priority due to ease of monitoring compared to other groups such as nematodes and potworms. Litter decomposition influences nutrient and carbon cycling, and provides insight into the microbial community (Guerra et al., 2021).

5 | STANDARDISED METHODOLOGIES FOR COLLECTING BIODIVERSITY AND SOIL METRICS IN THE UNITED KINGDOM

Once ecological metrics have been selected, well-designed data collection methods will ensure useful data are produced (Legg & Nagy, 2006; Lovett et al., 2007; Pocock et al., 2015). Methods should be consistent through time, accurate and follow accepted approaches, as field design and methods determine future analyses, statistical rigor and the research questions that can be addressed (Legg & Nagy, 2006; Lovett et al., 2007; Pocock et al., 2015). Standardised data collection enables between-project comparisons and alignment with regional or national monitoring efforts (Pocock et al., 2015).

To support practitioners in data collection, we identified standardised data collection methodologies for each metric. As part of the broader initiative to provide tools and guidance for NbS practitioners (Agile Initiative, n.d.), we focused on identifying UK-applicable methodologies, but many of the methods will be more widely applicable.

For biodiversity, standardised methodologies are most widely available to monitor specific species groups (Table S3). The United Kingdom has established methodologies for plants (National Plant Monitoring Scheme [NPMS, 2019]), butterflies (UK Butterfly Monitoring Scheme [UKBMS, 2021]) and birds (UK Breeding Bird Survey [BTO, 2022]). The UK Environmental Change Network (UKECN, 2022) provides methods for carabids, spiders, moths, bats, frogs, crane flies, spittle bugs and wild herbivores (rabbits & deer). Habitat classification based on characteristic plant species and communities is also possible, for example, using the UK Habitats Classification (UKHab Ltd., 2023). These methodologies support data collection for biodiversity metrics but often require additional steps not defined in the standardised methodology to calculate the final metric. For example, functional trait diversity can be calculated by linking trait information to data collected during species diversity surveys (Waldén et al., 2023). There are examples of scientific papers assessing functional trait diversity, and various databases with trait information for different species groups are available (e.g. Ecological Flora of Britain and Ireland http://ecoflora.org.uk/). Although this process has not been standardised, we included it in Tier 1 to represent the function axis of biodiversity and due to its high informativeness. There are also more developed standardised methodologies for a subset of biodiversity metrics relevant to woodland ecosystems (Table S3: Vegetation structure, Deadwood volume, Seedling regeneration, Tree age, Tree diversity and Vegetation biomass), which were developed for the UK National Forest Inventory (Forestry Commission, 2016a) and provide information on the full process from sampling design and data collection through to calculation of the derived metrics.

As the soil health concept is widely applied to agriculture (Griffiths et al., 2018), methodologies targeting farmers are available for many metrics, and are generally transferable to non-farm habitats (Table S4). The UK's Farm Carbon Toolkit provides information on sampling design (e.g. sample size, layout of samples and soil sampling depths) to assess soil carbon stocks, which can be applied to many other soil health metrics (Farm Carbon Toolkit, 2021). The Food and Agricultural Organisation of the United Nations' Global Soil Doctors Programme provides protocols for assessing many key soil health metrics (FAO, 2020). Methodologies for assessing biological aspects of soil health require more development to produce widely applicable, robust protocols, although some metrics have been assessed in scientific studies (Pulleman et al., 2012). Earthworms are a more accessible indicator and are used in the UK Centre for Ecology and Hydrology's benchmark for soil health (Feeney et al., 2023). The UK's Earthworm Watch Citizen Science project and UK's Agricultural and Horticultural Development Board provide protocols for monitoring using soil pits, which can be combined with the Farm Carbon Toolkit sample design recommendations (Burton et al., 2024; Stroud & Bennett, 2018). Other aspects of soil biodiversity are more complex to monitor, requiring greater expertise and having multiple possible methodologies. For example, fungal biomass can be estimated using phospholipid fatty acid, ergosterol or quantitative PCR analysis (Bünemann et al., 2018).

Data collection design (sampling, replication and frequency) determines what analysis is possible and therefore how useful the data are for monitoring (Ockendon et al., 2021). A point of comparison, for example, a baseline or counterfactual, is crucial to gain useful information from data collection (McGlone et al., 2020; Pocock et al., 2015). The gold standard is a Before-After-Control-Impact (BACI) study design, tracking the focal variables before and after an intervention, alongside monitoring at a control site (Christie et al., 2019). However, a BACI design requires a significant investment of time and resources, so simpler designs are often used. A Before-After (BA) design involves monitoring metrics before and after the interventions within the project site only (Christie et al., 2019; De Palma et al., 2018), but makes a major assumption that focal variables would not have changed without the intervention and does not account for variation resulting from other drivers (Christie et al., 2019; Wauchope et al., 2021). Ideally, projects would monitor a control site to determine whether observed changes result from project interventions (Wauchope et al., 2021). Long-term data collection allows assessment of metric trajectories over time (Wauchope et al., 2021), ideally compared to trends at comparator sites or threshold values. However, for many metrics, it was challenging to identify thresholds, and it was clear that the indication of positive or negative change would be context dependent, for example, an increase in vegetation biomass is not always desirable in grassland ecosystems (Tables S5 and S6).

6 | PRACTICAL APPLICATION OF THE FRAMEWORK—A CASE STUDY

The final set of metrics selected will be project-dependent; multiple ecosystem dimensions should be covered, but not all aspects need assessment to understand the overall ecological response, direction of change and whether project goals have been met (Andreasen et al., 2001). To aid selection, our framework is available on an interactive web platform (https://nbshub.naturebasedsolutionsinitiative.org/monitoring-outcomes/) where users can filter metrics by different criteria (Metric type, Aspect of biodiversity or soil health, Scale, Ecosystem, Cost, Technical Expertise and Standardised methodology; Figure 3). Once metrics have been selected, a sampling design and data collection plan can be developed for the project. Even when a standardised methodology is available, the sampling design will need to be adapted to the site layout and size. A User Guide developed alongside the framework provides guidance for creating a monitoring plan for an NbS project (Warner et al., 2024). In this section, we illustrate the application of our monitoring approach using a theoretical example of an NbS project in the United Kingdom, following the process in Figure 3. Our hypothetical case study restores arable land to a mix of woodland, species-rich grassland, and wetland (Figure 4), aiming to sequester carbon and slow the entry of water to the adjacent river to mitigate flooding. We outline a set of metrics representing different aspects of soil health and biodiversity at multiple scales to capture key responses in this project.

The project objectives require a method for tracking target habitat development and direct biodiversity monitoring to assess resulting changes in ecological communities. The carbon objectives of the project could be monitored by deriving carbon estimates from vegetation biomass and soil carbon monitoring. Finally, tracking the recovery of the soil from past cultivation and assessing its water-holding capacity would also be valuable. Monitoring other outcomes, such as flood risk and socio-economic impacts, is also important, but not covered here as this paper focuses on ecological indicators.

A starting point for biodiversity monitoring would be to track the establishment of the target habitats over time, classifying habitat types using the UK Habitats Classification (UKHab Ltd., 2023). Landscape diversity and more complex metrics such as habitat connectivity and fragmentation could be derived from the habitat data if this expertise was available in the project. Species-level surveys representing different parts of the community (e.g. plants, beetles and birds) could provide species diversity, identity and relative abundance metrics. If reference habitats representing the target habitats exist nearby, similarity to the target habitat for each community of organisms could be calculated either using existing data for those sites (if available) or by conducting additional surveys. Vegetation structure could be monitored to assess the development of the habitat and biomass, for example, by direct measurement of tree diameter at breast height, and above-ground carbon estimates can be derived from the same dataset (Broughton et al., 2021).

For soil health, bulk density could assess soil compaction changes with the withdrawal of cultivation, and enables volumetric conversion

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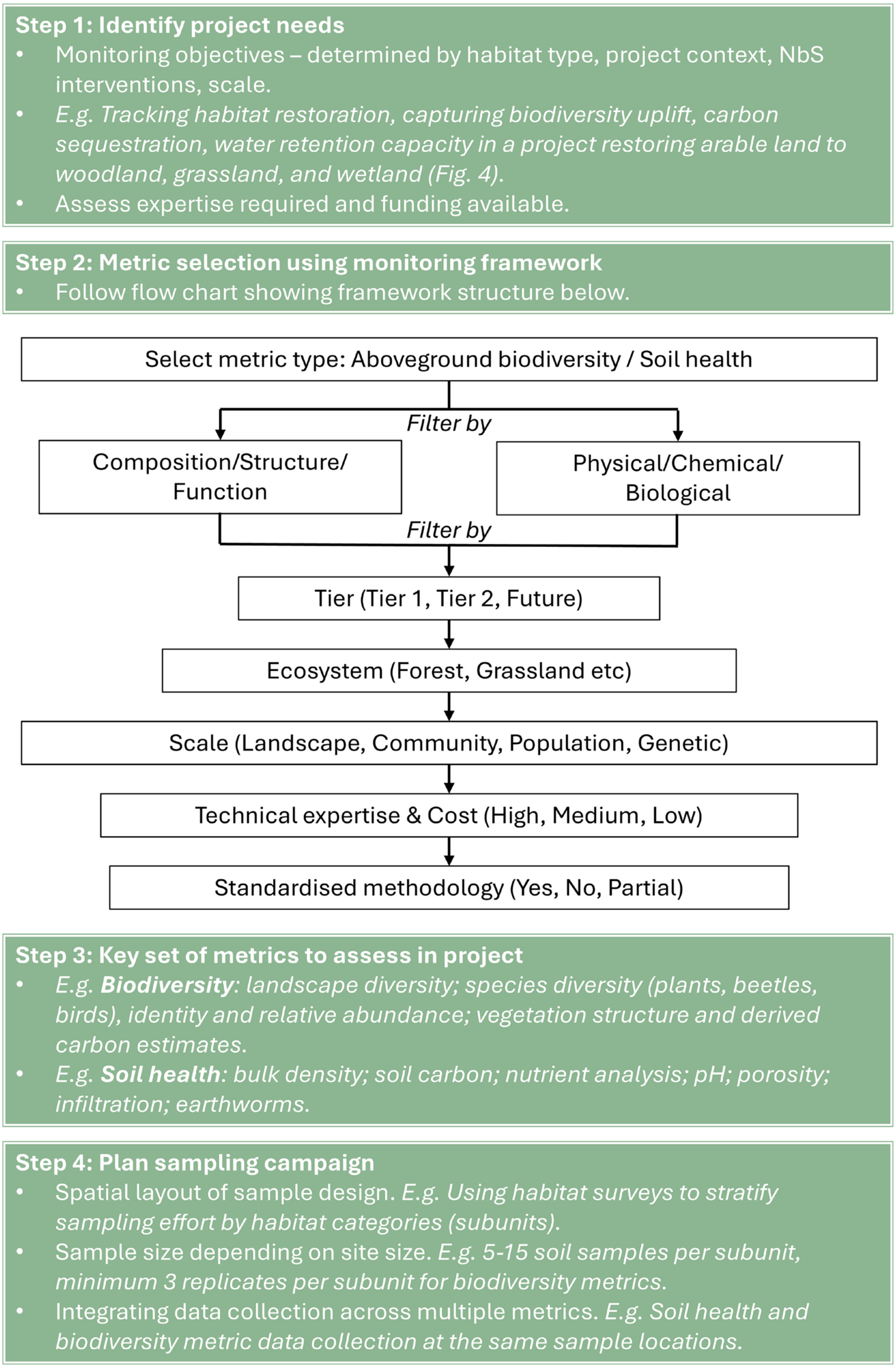

FIGURE 3 The steps involved in designing an ecological monitoring strategy for an NbS project. The flow chart in Step 2 captures the structure of the monitoring framework, available at https://nbshub.naturebasedsolutionsinitiative.org/monitoring-outcomes/. Examples drawing on our theoretical NbS project (Figure 4) are given for each step.

of soil carbon or nutrient analyses (Merrington, 2006). Soil carbon monitoring would evaluate carbon uptake with the return of semi-natural habitats, with a low soil carbon baseline expected after a history of arable cultivation (Smith, 2004; Smith et al., 2020). High nutrient loads after fertilisation of previous arable land could limit the development of botanically diverse semi-natural habitats (Cramer et al., 2008; Moeslund et al., 2023). Nitrogen and phosphorus (nutrient analysis) monitoring would track changes in nutrient availability; depending on prior agricultural management, the land may be suffering from nutrient enrichment or depletion, which can both influence the

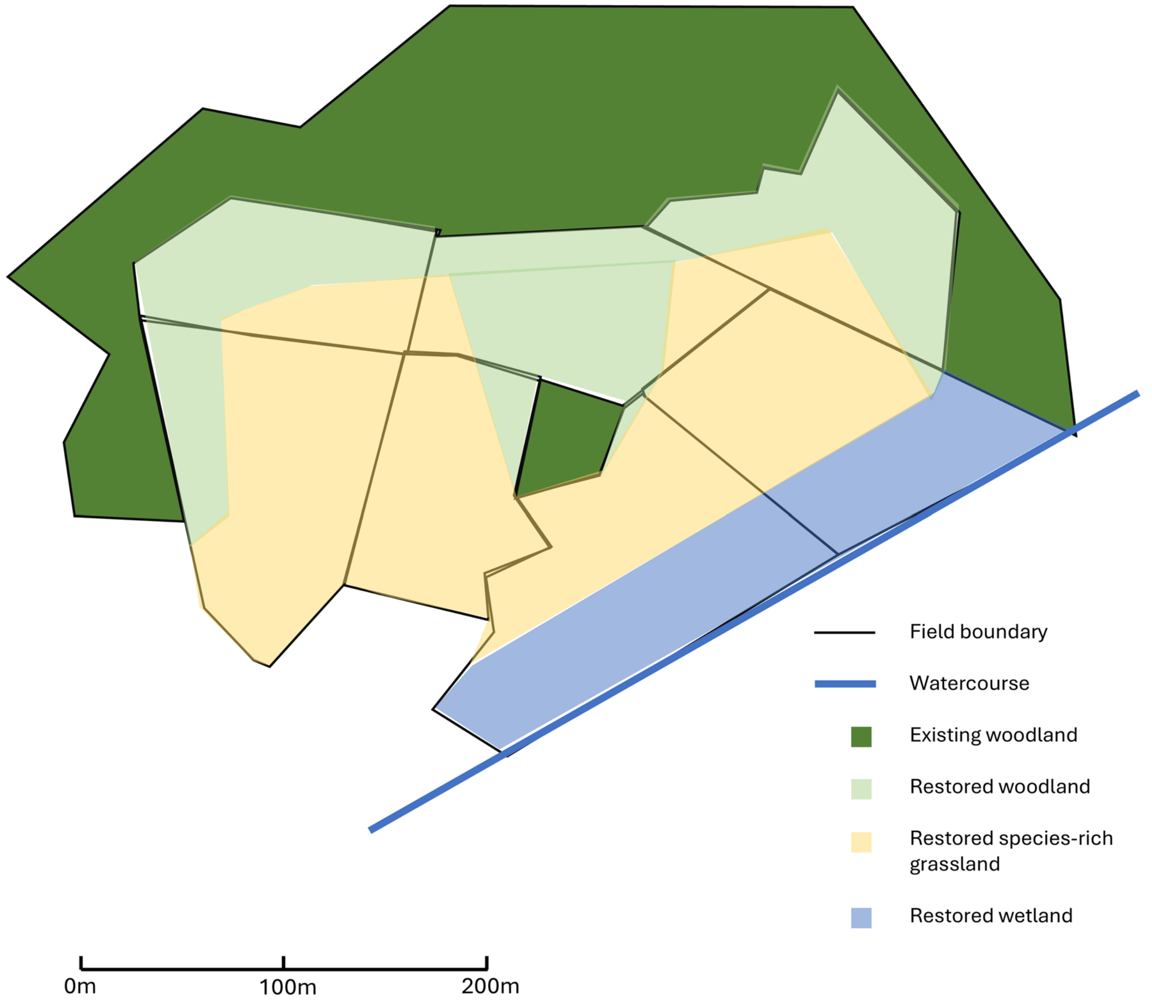

FIGURE 4 Schematic of a theoretical NbS project, showing the target habitats overlaid onto the existing field boundaries.

habitat restoration trajectory (Cramer et al., 2008; McLauchlan, 2006; Parkhurst et al., 2022). Soil pH would provide additional context to other soil health measures and also track soil recovery from agricultural activities (Cardoso et al., 2013). Given the focus on semi-natural habitat restoration for water retention, the porosity and infiltration of the soil will indicate its water-holding capacity and the recovery of desirable soil structure following cessation of agricultural disturbance (Cleophas et al., 2022; Lipiec et al., 2006). The most feasible biological indicator is earthworms (abundance/biomass/diversity), which are positively correlated with water infiltration rates as well as being an important group of soil organisms (Griffiths et al., 2018).

Once the target metrics are selected, a sampling design is developed. Ideally, data should be collected at the same spatial locations for all metrics to assess relationships between metrics. Habitat surveys conducted as part of the biodiversity monitoring approach provide the basis for developing the experimental design: The sample replicates can be stratified across each habitat area. In our theoretical case study site, the area is further subdivided into the former agricultural fields, which should also guide the sampling design, as their unique management histories may influence the trajectory of change in above- and below-ground ecological components after restoration. For the soil health metrics, the Farm Carbon Toolkit offers advice on sample size and layout, recommending 5–15 samples per sampling unit, so in this case, 5–15 samples in each habitat type-field combination (Farm Carbon Toolkit, 2021). The same soil samples can be used for the bulk density, soil carbon, soil nutrient and porosity analyses. The earthworm and infiltration sampling methodologies can be carried out at the same soil sample locations. The species-level surveys follow either a plot or transect approach. Our theoretical site is >10 ha in size, so we recommend a minimum of three replicates per sample sub-unit (habitat × field combination), following guidance from the UK Plant Monitoring Scheme for plants, UK Environmental Change Network for carabid beetles and UK Breeding Bird Survey for birds (BTO, 2022; NPMS, 2019; UKECN, 2022). Standardised protocols for assessing vegetation structure in woodland and modified grassland protocol suggest slightly different plot shapes and sizes, but data collection can be centred on the same locations as the species diversity plots (Forestry Commission, 2016b; Wood et al., 2012). An additional step to monitor changes in species identity would require the project to use functional trait databases to link relevant traits to the species-level data. For example, trait data from the Ecological Flora of Britain & Ireland (http://ecoflora.org.uk/) and data from previous studies, for example, Spake et al. (2016) could be linked to the species data. This adds an important additional layer of information on the functional element of biodiversity. In this example, changes in the target soil health indicators will correlate with the development of the target habitats, with reciprocal interactions between vegetation development and changes in soil carbon, nutrient status, physical structure and soil organisms (Farrell et al., 2020).

All monitoring programmes must balance time, cost and expertise constraints. Sampling intensity will be balanced against practical constraints, and further resources are associated with processing samples (chemical analysis, identifying specimens) and subsequent data analysis (Mandelik et al., 2010; Weiser et al., 2019). If expertise is limited, biodiversity data collection may be restricted to more easily identifiable species groups and metrics with simpler field protocols, whereas many of the soil metrics have relatively simple sample collection approaches, using laboratories for the technical soil analysis. Community involvement, citizen science, and university partnerships can help offset costs (Pocock et al., 2018). Practitioners should prioritise Tier 1 metrics, as they are most informative and feasible. Under resource constraints, selecting metrics with existing standardised methodologies ensures efficiency and comparability (Griffiths et al., 2018). A phased approach can be adopted, starting with essential indicators and expanding as capacity increases. Using standardised protocols and low-cost, portable technologies reduces expenses, while supportive policies, financial incentives, better links between scientists and practitioners, and training enhance scalability and equity (Giuliani et al., 2024; Schmeller et al., 2017). Future innovations that reduce the financial or practical investment in monitoring have the potential to increase the overall feasibility of monitoring.

Field data collection is followed by analysis. Ideally, metrics would be compared to known thresholds indicating positive or negative change; however, these are not available in many cases (Tables S5 and S6). Nationwide trends or data collected from reference sites offer potential alternative points of comparison.

7 | TECHNOLOGICAL INNOVATIONS TO INCREASE MONITORING FEASIBILITY

Interest in technological advances to simplify and reduce the costs of ecological monitoring is growing. The most widely proposed innovations include remote sensing, acoustic monitoring, environmental DNA (eDNA) and artificial intelligence (AI) (Ford et al., 2024; Van Klink et al., 2024). Understanding their potential to replace traditional ecological data collection methods and the necessary developments to do so is essential (Besson et al., 2022). During the literature review process, we identified emerging technologies to enhance or replace traditional data collection (Tables S7 and S8). Remote sensing, acoustic monitoring and eDNA all have the potential to significantly reduce fieldwork effort and bypass expertise constraints, particularly taxonomic knowledge required to identify more challenging groups of organisms.

Remote-sensed Earth Observation (EO) data can quantify taxonomic, structural and functional biodiversity metrics at multiple scales (Lausch et al., 2016). Spaceborne and airborne EO sensors can detect a wide range of spectral signals (optical, thermal and radar) and information can also be captured using lasers (Lausch et al., 2016). A large focus of EO has been capturing plant spectral traits ranging from biochemical and biophysical to functional and morphological (Frye et al., 2021; Lausch et al., 2016; Schweiger et al., 2018). These traits serve as proxies for plant species and communities, ecological processes and by extension wider aspects of the ecological community (Lausch et al., 2016). The accuracy of the relationship between the spectral traits and variables of interest depends on the sensor used, species characteristics and assumptions used to fit the remote-sensed data (Lausch et al., 2016). Some animal traits—morphological, physiological, phenotypic and activity—can be captured, depending on body size and sensor resolution (Lausch et al., 2016). Habitat area, configuration and diversity metrics can also be calculated from high-resolution remote-sensed imagery (Price et al., 2023; Sittaro et al., 2022). Structural data collected using LiDAR can be translated into vegetation structure and biomass metrics (Broughton et al., 2022; Jucker et al., 2023). Availability of space-collected biodiversity data is increasing, and structural and functional metrics are currently the most feasible to monitor (Pettorelli et al., 2016; Skidmore et al., 2021; Skidmore & Pettorelli, 2015). Spectral, thermal and radar data collection and modelling approaches are similarly applied to soil health monitoring, capturing metrics such as soil texture, moisture, and soil organic matter and carbon (Abdulraheem et al., 2023). Remote sensing to assess soil health offers the advantage of capturing variables over large areas and long time frames without the need for intensive soil sampling; however, there are still limitations in assessing deeper soil layers and in relating the indirect data collected to the focal metrics (Abdulraheem et al., 2023).

eDNA identifies the organisms present in an ecosystem by extracting DNA from an environmental sample such as water or soil (Bohmann et al., 2014). Sensitivity varies by taxon, but it can provide advances for cryptic or hard-to-identify species, although contamination risks must be managed to reduce false positives (Fediajevaite et al., 2021). eDNA analysis does not provide abundance data, so combining it with traditional methods could increase its impact (Deiner et al., 2017; Pereira et al., 2021). Resolution depends on reference database completeness, which varies geographically and taxonomically (Keck et al., 2023). Processing samples, dataset curation and analysis require specialist skills. Although commercial companies offer this service, cost can be a significant barrier: Depending on detection rates and sampling methods, traditional species monitoring can be more cost-effective (Larson et al., 2020; Smart et al., 2016). Directly metabarcoding plant or animal samples (e.g. a pitfall trap sample of many invertebrates) uses similar approaches to eDNA analysis, aiding identification of taxonomically challenging groups, for example, invertebrates (Kirse et al., 2021).

Passive acoustic monitoring captures ecological soundscapes and is relatively low cost and easy-to-deploy (Ford et al., 2024). The data represents vocal species (e.g. bird songs/calls, cricket chirps and bees buzzing) and post-processing generates species richness estimates and occupancy models (Ford et al., 2024; Sethi et al., 2023). Producing species richness metrics from acoustic data requires extensive training data for comparison and models can only detect vocalisations from well-characterised, common species (Sethi et al., 2023). There is also interest in overall soundscape metrics that, for example, can be used to compare restored ecosystems to a reference state (Sethi et al., 2020). These rely on complex modelling methods such as convolutional neural networks (Sethi et al., 2020). Whole-system metrics can correlate positively with biodiversity at a site; however, these relationships are not consistent across multiple sites, limiting their wide applicability (Sethi et al., 2023). Therefore, acoustic monitoring is conducted most usefully alongside traditional ecological monitoring (Sethi et al., 2023). Soundscape monitoring can also be applied below-ground, and a recent study found a correlation between acoustic diversity and invertebrate abundance, but not richness (Robinson et al., 2023). Soil soundscape monitoring needs more development and refinement, as currently sounds produced by living organisms cannot easily be distinguished from sounds generated by physical soil movement, and there are limited reference datasets (Metcalf et al., 2023; Robinson et al., 2023).

Large, complex multi-dimensional datasets generated by remote sensing, eDNA and acoustic monitoring require more sophisticated, technical and time-consuming data-processing and analysis methods (Besson et al., 2022). Modelling approaches such as computer audition and vision packages, and machine learning could provide the final step of producing derived metrics in a fully automated biodiversity monitoring system (Besson et al., 2022). Large, properly labelled training datasets will be key to expanding automated monitoring across ecosystems at multiple scales (Besson et al., 2022; van Klink et al., 2022). Currently, the technological approaches discussed also require standardisation of the data collection methodology; for example, sensor deployment conformation, and accessibility to practitioners may be limited by training needs and costs (Schmeller et al., 2017). The feasibility of monitoring using remote sensing and eDNA depends on project scale, taxa and expertise (Deiner et al., 2017), LiDAR for vegetation is well established (Jucker et al., 2023), while soil soundscape monitoring is still developing (Robinson et al., 2023). Integrating traditional methods with targeted technological applications can enhance NbS monitoring while balancing feasibility, cost and data reliability (Van Klink et al., 2024).

We envision projects increasingly using a mixture of technological and conventional approaches to ecological monitoring. In our example project (Figure 4), acoustic and eDNA monitoring could capture the species diversity metrics for birds, invertebrates and soil communities, and remote sensing could capture habitat development, vegetation structure and proxy variables for plant functional trait diversity (Lausch et al., 2016). However, high expertise is needed to process and interpret remote-sensed plant trait and structure data, reducing accessibility to practitioners unless collaboration with scientific researchers is possible (Marvin et al., 2016). Most of the physical and chemical soil metrics will rely on conventional field sampling methods (Marvin et al., 2016).

8 | CONCLUSIONS

A monitoring approach integrating above- and below-ground ecological metrics is highly desirable for NbS, given the interdependencies between above- and below-ground ecological processes (Chomel et al., 2022; Farrell et al., 2020). From numerous possible metrics, we highlight the most informative and feasible to monitor, while acknowledging practical constraints on optimal monitoring. Existing standardised methodologies can be adapted for simultaneous biodiversity and soil health monitoring. However, barriers to implementation include a lack of reference values or thresholds for many metrics, and in some cases, a lack of standardised data collection methodologies. Emerging technologies may simplify technically demanding approaches to metric generation but will most likely complement traditional ecological monitoring. Ultimately, monitoring is project-dependent, and our framework provides high-level guidance on metric selection and data collection design that can be refined to meet project-specific goals. While our framework is UK focused, the metrics and, in many cases, standardised data collection approaches are widely applicable internationally.

AUTHOR CONTRIBUTIONS

Emily Warner conceived the idea, which was developed and refined with Licida M. Giuliani, Grant A. Campbell, Pete Smith, Alison C. Smith and Nathalie Seddon. Emily Warner, Licida M. Giuliani and Grant A. Campbell conducted the literature review and developed the metric prioritisation methodology. Pete Smith, Alison C. Smith and Nathalie Seddon provided feedback on the metric selection process and the resulting set of metrics. Dan Seddon designed and developed the online version of the monitoring framework. Emily Warner led the writing with input from all authors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70043.

DATA AVAILABILITY STATEMENT

The monitoring framework is available at: https://nbshub.naturebasedsolutionsinitiative.org/monitoring-tool/ (Agile Initiative, 2025).

RELEVANT GREY LITERATURE

You can find related grey literature on the topics below on Applied Ecology Resources: Biodiversity, ecological monitoring, nature-based solutions.

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REFERENCES

Abdulraheem, M. I., Zhang, W., Li, S., Moshayedi, A. J., Farooque, A. A., & Hu, J. (2023). Advancement of remote sensing for soil measurements and applications: A comprehensive review. *Sustainability*, *15*(21), 15444. https://doi.org/10.3390/su152115444

Agile Initiative. (2025). Monitoring NbS Outcomes. https://nbshub.naturebasedsolutionsinitiative.org/monitoring-outcomes/

Agile Initiative. (n.d.). How do we scale up Nature-based Solutions? https://www.agile-initiative.ox.ac.uk/sprints/how-do-we-scale-up-nature-based-solutions/

Andreasen, J. K., O'Neill, R. V., Noss, R., & Slosser, N. C. (2001). Considerations for the development of a terrestrial index of ecological integrity. *Ecological Indicators*, *1*, 21–35.

Barrios, E. (2007). Soil biota, ecosystem services and land productivity. *Ecological Economics*, *64*, 269–285.

Besson, M., Alison, J., Bjerge, K., Gorochowski, T. E., Høye, T., Jucker, T., Mann, H., & Clements, C. (2022). Towards the fully automated monitoring of ecological communities. *Authorea*, 566410.

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B. C., Munda, S., & Dari, B. (2022). A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology*, *13*, 938481.

Bohmann, K., Evans, A., Gilbert, M. T. P., Carvalho, G. R., Creer, S., Knapp, M., Yu, D. W., & de Bruyn, M. (2014). Environmental DNA for wildlife biology and biodiversity monitoring. *Trends in Ecology & Evolution*, *29*(6), 358–367. https://doi.org/10.1016/j.tree.2014.04.003

Broughton, R. K., Bullock, J. M., George, C., Gerard, F., Maziarz, M., Payne, W. E., Scholefield, P. A., Wade, D., & Pywell, R. F. (2022). Slow development of woodland vegetation and bird communities during 33 years of passive rewilding in open farmland. *PLoS One*, *17*, 1–19.

Broughton, R. K., Bullock, J. M., George, C., Hill, R. A., Hinsley, S. A., Maziarz, M., Melin, M., Mountford, J. O., Sparks, T. H., & Pywell, R. F. (2021). Long-term woodland restoration on lowland farmland through passive rewilding. *PLoS One*, *16*, e0252466.

BTO. (2022). Breeding bird survey.

Buckland, S. T., Magurran, A. E., Green, R. E., & Fewster, R. M. (2005). Monitoring change in biodiversity through composite indices. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *360*, 243–254.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., de Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality—A critical review. *Soil Biology and Biochemistry*, *120*, 105–125.

Burton, V. J., Jones, A. G., Robinson, L. D., Eggleton, P., & Purvis, A. (2024). Earthworm watch: Insights into urban earthworm communities in the UK using citizen science. *European Journal of Soil Biology*, *121*, 103622.

Cardoso, E. J. B. N., Vasconcellos, R. L. F., Bini, D., Miyauchi, M. Y. H., Santos, C. A., Alves, P. R. L., Paula, A. M., Nakatani, A. S., Pereira, J. M., & Nogueira, M. A. (2013). Soil health: Looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? *Scientia Agricola*, *70*, 274–289.

Carignan, V., & Villard, M. (2002). Selecting indicator species to monitor ecological integrity: A review. *Ecological Monitoring & Assessment*, *78*, 45–61.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, *26*, 6134–6155.

Chomel, M., Lavallee, J. M., Alvarez-Segura, N., Baggs, E. M., Caruso, T., de Castro, F., Emmerson, M. C., Magilton, M., Rhymes, J. M., de Vries, F. T., Johnson, D., & Bardgett, R. D. (2022). Intensive grassland management disrupts below-ground multi-trophic resource transfer in response to drought. *Nature Communications*, *13*, 1–12.

Christie, A. P., Amano, T., Martin, P. A., Shackelford, G. E., Simmons, B. I., & Sutherland, W. J. (2019). Simple study designs in ecology produce inaccurate estimates of biodiversity responses. *Journal of Applied Ecology*, *56*, 2742–2754.

Cleophas, F., Isidore, F., Musta, B., Mohd Ali, B. N., Mahali, M., Zahari, N. Z., & Bidin, K. (2022). Effect of soil physical properties on soil infiltration rates. *Journal of Physics*, *2314*, 012020.

Cosović, M., Bugalho, M. N., Thom, D., & Borges, J. G. (2020). Stand structural characteristics are the most practical biodiversity indicators for forest management planning in Europe. *Forests*, *11*, 343.

Cramer, V. A., Hobbs, R. J., & Standish, R. J. (2008). What's new about old fields? Land abandonment and ecosystem assembly. *Trends in Ecology & Evolution*, *23*(2), 104–112. https://doi.org/10.1016/j.tree.2007.10.005

Czúcz, B., Keith, H., Maes, J., Driver, A., Jackson, B., Nicholson, E., Kiss, M., & Obst, C. (2021). Selection criteria for ecosystem condition indicators. *Ecological Indicators*, *133*, 108376.

Dangerfield, J. M., Pik, A. J., Britton, D., Holmes, A., Gillings, M., Oliver, I., Briscoe, D., & Beattie, A. J. (2003). Patterns of invertebrate biodiversity across a natural edge. *Austral Ecology*, *28*, 227–236.

De Palma, A., Sanchez-Ortiz, K., Martin, P. A., Chadwick, A., Gilbert, G., Bates, A. E., Börger, L., Contu, S., Hill, S. L. L., & Purvis, A. (2018). *Challenges with inferring how land-use affects terrestrial biodiversity: Study design, time, space and synthesis* (1st ed.). Elsevier Ltd.

Deane, D. C., Nozohourmehrabad, P., Boyce, S. S. D., & He, F. (2020). Quantifying factors for understanding why several small patches host more species than a single large patch. *Biological Conservation*, *249*, 108711.

Deiner, K., Bik, H. M., Mächler, E., Seymour, M., Lacoursière-Roussel, A., Altermatt, F., Creer, S., Bista, I., Lodge, D. M., de Vere, N., Pfrender, M. E., & Bernatchez, L. (2017). Environmental DNA metabarcoding: Transforming how we survey animal and plant communities. *Molecular Ecology*, *26*, 5872–5895.

Donatti, C. I., Andrade, A., Cohen-Shacham, E., Fedele, G., Hou-Jones, X., & Robyn, B. (2022). Ensuring that nature-based solutions for climate mitigation address multiple global challenges. *One Earth*, *5*, 493–504.

Dumitru, A., & Wendling, L. (2021). *Evaluating the impact of nature-based solutions —A handbook for practitioners*. European Commission. https://doi.org/10.2777/244577

FAO. (2020). *Soil testing methods manual*. FAO.

Farm Carbon Toolkit. (2021). *Monitoring soil carbon: A practical field, farm and lab guide*.

Farrell, H. L., Léger, A., Breed, M. F., & Gornish, E. S. (2020). Restoration, soil organisms, and soil processes: Emerging approaches. *Restoration Ecology*, *28*, S307–S310.

Fediajevaite, J., Priestley, V., Arnold, R., & Savolainen, V. (2021). Meta-analysis shows that environmental DNA outperforms traditional surveys, but warrants better reporting standards. *Ecology and Evolution*, *11*, 4803–4815.

Feeney, C. J., Robinson, D. A., Keith, A. M., Vigier, A., Bentley, L., Smith, R. P., Garbutt, A., Maskell, L. C., Norton, L., Wood, C. M., Cosby, B. J., & Emmett, B. A. (2023). Development of soil health benchmarks for managed and semi-natural landscapes. *Science of the Total Environment*, *886*, 163973.

Feld, C. K., Martins da Silva, P., Paulo Sousa, J., de Bello, F., Bugter, R., Grandin, U., Hering, D., Lavorel, S., Mountford, O., Pardo, I., Pärtel, M., Römbke, J., Sandin, L., Bruce Jones, K., & Harrison, P. (2009). Indicators of biodiversity and ecosystem services: A synthesis across ecosystems and spatial scales. *Oikos*, *118*, 1862–1871.

Ford, H. V., Schrodt, F., Zieritz, A., Exton, D. A., van der Heijden, G., Teague, J., Coles, T., & Field, R. (2024). A technological biodiversity monitoring toolkit for biocredits. *Journal of Applied Ecology*, *61*, 1–13.

Forestry Commission. (2016a). Chapter 1: Introduction. In *NFI survey manual* (pp. 1–10). Forestry Commission.

Forestry Commission. (2016b). Tree assessment procedures. In *NFI survey manual* (pp. 1–21). Forestry Commission.

Frye, H. A., Aiello-Lammens, M. E., Euston-Brown, D., Jones, C. S., Kilroy Mollmann, H., Merow, C., Slingsby, J. A., van der Merwe, H., Wilson, A. M., & Silander, J. A., Jr. (2021). Plant spectral diversity as a surrogate for species, functional and phylogenetic diversity across a hyper-diverse biogeographic region. *Global Ecology and Biogeography*, *30*, 1403–1417.

Giuliani, L. M., Warner, E., Campbell, G. A., Lynch, J., Smith, A. C., & Smith, P. (2024). Advancing nature—based solutions through enhanced soil health monitoring in the United Kingdom. *Soil Use and Management*, *40*, 1–18.

Griffiths, B. S., Faber, J., & Bloem, J. (2018). Applying soil health indicators to encourage sustainable soil use: The transition from scientific study to practical application. *Sustainability*, *10*, 3021.

Griffiths, B. S., Römbke, J., Schmelz, R. M., Scheffczyk, A., Faber, J. H., Bloem, J., Pérès, G., Cluzeau, D., Chabbi, A., Suhadolc, M., Sousa, J. P., Martins da Silva, P., Carvalho, F., Mendes, S., Morais, P., Francisco, R., Pereira, C., Bonkowski, M., Geisen, S., … Stone, D. (2016). Selecting cost effective and policy-relevant biological indicators for European monitoring of soil biodiversity and ecosystem function. *Ecological Indicators*, *69*, 213–223.

Guerra, C. A., Bardgett, R. D., Caon, L., Crowther, T. W., Montanarella, L., Navarro, L. M., Orgiazzi, A., Singh, B. K., Tedersoo, L., Vargas-rojas, R., Briones, M. J. I., Buscot, F., Cameron, E. K., Cesarz, S., Chatzinotas, A., Cowan, D. A., Djukic, I., Van Den Hoogen, J., Maestre, F. T., … Eisenhauer, N. (2021). Tracking, targeting, and conserving soil biodiversity: A monitoring and indicator system can inform policy. *Science*, *371*, 239–241.

Guo, M. (2021). Soil health assessment and management: Recent development in science and practices. *Soil Systems*, *5*, 61.

Harris, M., Hoskins, H., Robinson, A., Hutchison, J., Withers, A., Deeks, L., Hannam, J., Harris, J., Way, L., & Rickson, J. (2023). *JNCC report 737 towards indicators of soil health*. JNCC.

Heink, U., & Kowarik, I. (2010). What criteria should be used to select biodiversity indicators? *Biodiversity and Conservation*, *19*, 3769–3797.

Hillebrand, H., Blasius, B., Borer, E. T., Chase, J. M., Downing, J. A., Eriksson, B. K., Filstrup, C. T., Harpole, W. S., Hodapp, D., Larsen, S., Lewandowska, A. M., Seabloom, E. W., van de Waal, D. B., & Ryabov, A. B. (2018). Biodiversity change is uncoupled from species richness trends: Consequences for conservation and monitoring. *Journal of Applied Ecology*, *55*, 169–184.

Hines, J., & Pereira, H. M. (2021). Biodiversity: Monitoring trends and implications for ecosystem functioning. *Current Biology*, *31*, R1390–R1392.

IUCN. (2020). *Guidance for using the IUCN Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design, and scaling up of Nature-based Solutions*. IUCN. https://doi.org/10.2305/iucn.ch.2020.09.en

Jian, J., Du, X., & Stewart, R. D. (2020). A database for global soil health assessment. *Scientific Data*, *7*, 3–10.

Jucker, T., Gosper, C. R., Wiehl, G., Yeoh, P. B., Raisbeck-Brown, N., Fischer, F. J., Graham, J., Langley, H., Newchurch, W., O'Donnell, A. J., Page, G. F. M., Zdunic, K., & Prober, S. M. (2023). Using multi-platform LiDAR to guide the conservation of the world's largest temperate woodland. *Remote Sensing of Environment*, *296*, 113745.

Karr, J. R., & Dudley, D. R. (1981). Ecological perspective on water quality goals. *Environmental Management*, *5*(1), 55–68. https://doi.org/10.1007/BF01866609

Karr, J. R., Larson, E. R., & Chu, E. W. (2022). Ecological integrity is both real and valuable. *Conservation Science and Practice*, *4*(2), 1–10. https://doi.org/10.1111/csp2.583

Keck, F., Couton, M., & Altermatt, F. (2023). Navigating the seven challenges of taxonomic reference databases in metabarcoding analyses. *Molecular Ecology Resources*, *23*, 742–755.

Key, I. B., Smith, A. C., Turner, B., Chausson, A., Girardin, C. A. J., Macgillivray, M., & Seddon, N. (2022). Biodiversity outcomes of nature-based solutions for climate change adaptation: Characterising the evidence base. *Frontiers in Environmental Science*, *10*, 905767. https://doi.org/10.3389/fenvs.2022.905767

Kirse, A., Bourlat, S. J., Langen, K., & Fonseca, V. G. (2021). Metabarcoding Malaise traps and soil eDNA reveals seasonal and local arthropod diversity shifts. *Scientific Reports*, *11*, 1–12.

Knight, K. B., Seddon, E. S., & Toombs, T. P. (2020). A framework for evaluating biodiversity mitigation metrics. *Ambio*, *49*(6), 1232–1240. https://doi.org/10.1007/s13280-019-01266-y

Larson, E. R., Graham, B. M., Achury, R., Coon, J. J., Daniels, M. K., Gambrell, D. K., Jonasen, K. L., King, G. D., LaRacuente, N., Perrin-Stowe, T. I. N., Reed, E. M., Rice, C. J., Ruzi, S. A., Thairu, M. W., Wilson, J. C., & Suarez, A. V. (2020). From eDNA to citizen science: Emerging tools for the early detection of invasive species. *Frontiers in Ecology and the Environment*, *18*(4), 194–202. https://doi.org/10.1002/fee.2162

Lausch, A., Bannehr, L., Beckmann, M., Boehm, C., Feilhauer, H., Hacker, J. M., Heurich, M., Jung, A., Klenke, R., Neumann, C., Pause, M., Rocchini, D., Schaepman, M. E., Schmidtlein, S., Schulz, K., Selsam, P., Settele, J., Skidmore, A. K., & Cord, A. F. (2016). Linking earth observation and taxonomic, structural and functional biodiversity: Local to ecosystem perspectives. *Ecological Indicators*, *70*, 317–339.

Legg, C. J., & Nagy, L. (2006). Why most conservation monitoring is, but need not be, a waste of time. *Journal of Environmental Management*, *78*, 194–199.

Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., & Nosalewicz, A. (2006). Soil porosity and water infiltration as influenced by tillage methods. *Soil and Tillage Research*, *89*, 210–220.

Loveland, P., & Thompson, T. (2002). Identification and development of a set of national indicators for soil quality. R&D Project P5-053, Report P5-053/02/PR. Bristol.

Lovett, G. M., Burns, D. A., Driscoll, C. T., Jenkins, J. C., Mitchell, M. J., Rustad, L., Shanley, J. B., Likens, G. E., & Haeuber, R. (2007). Who needs environmental monitoring? *Frontiers in Ecology and the Environment*, *5*, 253–260.

Lyashevska, O., & Farnsworth, K. D. (2012). How many dimensions of biodiversity do we need? *Ecological Indicators*, *18*, 485–492.

Mallette, A., Plummer, R., & Baird, J. (2022). Assessing ecological conditions for landscape management: A comparative analysis of field measurements and perceptions. *Landscape Research*, *47*, 695–711.

Mandelik, Y., Roll, U., & Fleischer, A. (2010). Cost-efficiency of biodiversity indicators for Mediterranean ecosystems and the effects of socio-economic factors. *Journal of Applied Ecology*, *47*, 1179–1188.

Marvin, D. C., Koh, L. P., Lynam, A. J., Wich, S., Davies, A. B., Krishnamurthy, R., Stokes, E., Starkey, R., & Asner, G. P. (2016). Integrating technologies for scalable ecology and conservation.

Global Ecology and Conservation, *7*, 262–275. https://doi.org/10.1016/j.gecco.2016.07.002
Maskell, L. C., Botham, M., Henrys, P., Jarvis, S., Maxwell, D., Robinson, D. A., Rowland, C. S., Siriwardena, G., Smart, S., Skates, J., Tebbs, E. J., Tordoff, G. M., & Emmett, B. A. (2019). Exploring relationships between land use intensity, habitat heterogeneity and biodiversity to identify and monitor areas of high nature value farming. *Biological Conservation*, *231*, 30–38.
McGlone, M., McNutt, K., Richardson, S., Bellingham, P., & Wright, E. (2020). Biodiversity monitoring, ecological integrity, and the design of the New Zealand biodiversity assessment framework. *New Zealand Journal of Ecology*, *44*, 3411.
McLauchlan, K. (2006). The nature and longevity of agricultural impacts on soil carbon and nutrients: A review. *Ecosystems*, *9*, 1364–1382.
Merrington, G., Fishwick, S., Barraclough, D., Morris, J., Preedy, N., Boucard, T., Reeve, M., Smith, P., & Fang, C. (2006). *The development and use of soil quality indicators for assessing the role of soil in environmental interactions*. Environment Agency.
Metcalf, O., Baccaro, F., Barlow, J., Berenguer, E., Bradfer-Lawrence, T., Rossi, L. C., Marinh do Vale, É., & Lees, A. (2023). Listening to tropical forest soils. *Ecological Indicators*, *158*, 31–41.
Moeslund, J. E., Andersen, D. K., Brunbjerg, A. K., Bruun, H. H., Fløjgaard, C., McQueen, S. N., Nygaard, B., & Ejrnæs, R. (2023). High nutrient loads hinder successful restoration of natural habitats in freshwater wetlands. *Restoration Ecology*, *31*, 1–13.
Morelli, F., Pruscini, F., Santolini, R., Perna, P., Benedetti, Y., & Sisti, D. (2013). Landscape heterogeneity metrics as indicators of bird diversity: Determining the optimal spatial scales in different landscapes. *Ecological Indicators*, *34*, 372–379.
Niemi, G. J., & McDonald, M. E. (2004). Application of ecological indicators. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 89–111.
Noss, R. F. (1990). Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology*, *4*, 355–364.
NPMS. (2019). *National plant monitoring scheme*.
Ockendon, N., et al. (2021). Effectively integrating experiments into conservation practice. *Ecological Solutions and Evidence*, *2*, 1–11.
Parkhurst, T., Prober, S. M., Hobbs, R. J., & Standish, R. J. (2022). Global meta-analysis reveals incomplete recovery of soil conditions and invertebrate assemblages after ecological restoration in agricultural landscapes. *Journal of Applied Ecology*, *59*, 358–372.
Pereira, C. L., Gilbert, M. T. P., Araújo, M. B., & Matias, M. G. (2021). Fine-tuning biodiversity assessments: A framework to pair eDNA metabarcoding and morphological approaches. *Methods in Ecology and Evolution*, *12*, 2397–2409.
Pettorelli, N., Wegmann, M., Skidmore, A., Mücher, S., Dawson, T. P., Fernandez, M., Lucas, R., Schaepman, M. E., Wang, T., O'Connor, B., Jongman, R. H. G., Kempeneers, P., Sonnenschein, R., Leidner, A. K., Böhm, M., He, K. S., Nagendra, H., Dubois, G., Fatoyinbo, T., … Geller, G. N. (2016). Framing the concept of satellite remote sensing essential biodiversity variables: Challenges and future directions. *Remote Sensing in Ecology and Conservation*, *2*, 122–131.
Pocock, M. J. O., Newson, S. E., Henderson, I. G., Peyton, J., Sutherland, W. J., Noble, D. G., Ball, S. G., Beckmann, B. C., Biggs, J., Brereton, T., Bullock, D. J., Buckland, S. T., Edwards, M., Eaton, M. A., Harvey, M. C., Hill, M. O., Horlock, M., Hubble, D. S., Julian, A. M., … Roy, D. B. (2015). Developing and enhancing biodiversity monitoring programmes: A collaborative assessment of priorities. *Journal of Applied Ecology*, *52*, 686–695.
Pocock, M. J. O., Chandler, M., Bonney, R., Thornhill, I., Albin, A., August, T., Bachman, S., Brown, P. M. J., Cunha, D., Gasparini, F., Grez, A., Jackson, C., Peters, M., Rabarijaon, N. R., Roy, H. E., Zaviezo, T., & Danielsen, F. (2018). Chapter six – a vision for global biodiversity monitoring with citizen science. In D. A. Bohan, A. J. Dumbrell, G. Woodward, & M. B. T.-. A. Jackson (Eds.), *Next generation biomonitoring: Part 2* (Vol. *59*, pp. 169–223). Academic Press.
Price, B., Huber, N., Nussbaumer, A., & Ginzler, C. (2023). The habitat map of Switzerland: A remote sensing, composite approach for a high spatial and thematic resolution product. *Remote Sensing*, *15*(3), 643. https://doi.org/10.3390/rs15030643
Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., & Rutgers, M. (2012). Soil biodiversity, biological indicators and soil ecosystem services-an overview of European approaches. *Current Opinion in Environmental Sustainability*, *4*, 529–538.
Robinson, J. M., Breed, M. F., & Abrahams, C. (2023). The sound of restored soil: Measuring soil biodiversity in a forest restoration chronosequence with ecoacoustics. *Restoration Ecology 31*(5), e13934.
Romanelli, J. P., Meli, P., Naves, R. P., Alves, M. C., & Rodrigues, R. R. (2021). Reliability of evidence-review methods in restoration ecology. *Conservation Biology*, *35*(1), 142–154. https://doi.org/10.1111/cobi.13661
Schmeller, D. S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N., Chandler, M., Chatzinikolaou, E., Costello, M. J., Ding, H., García-Moreno, J., Gill, M., Haase, P., Jones, M., Juillard, R., Magnusson, W. E., Martin, C. S., McGeoch, M., Mihoub, J.-B., Pettorelli, N., … Belnap, J. (2017). Building capacity in biodiversity monitoring at the global scale. *Biodiversity and Conservation*, *26*(12), 2765–2790. https://doi.org/10.1007/s10531-017-1388-7
Schoenholtz, S. H., Van Miegroet, H., & Burger, J. A. (2000). A review of chemical and physical properties as indicators of forest soil quality: Challenges and opportunities. *Forest Ecology and Management*, *138*(1-3), 335–356. https://doi.org/10.1016/S0378-1127(00)00423-0
Schweiger, A. K., Cavender-Bares, J., Townsend, P. A., Hobbie, S. E., Madritch, M. D., Wang, R., Tilman, D., & Gamon, J. A. (2018). Plant spectral diversity integrates functional and phylogenetic components of biodiversity and predicts ecosystem function. *Nature Ecology & Evolution*, *2*(6), 976–982. https://doi.org/10.1038/s41559-018-0551-1
Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *375*, 20190120.
Seddon, N., Turner, B., Berry, P., Chausson, A., & Girardin, C. A. J. (2019). Grounding nature-based climate solutions in sound biodiversity science. *Nature Climate Change*, *9*, 84–87.
Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., & Turner, B. (2021). Getting the message right on nature-based solutions to climate change. *Global Change Biology*, *27*, 1–29.
Sethi, S. S., Bick, A., Ewers, R. M., Klinck, H., Ramesh, V., Tuanmu, M. N., & Coomes, D. A. (2023). Limits to the accurate and generalizable use of soundscapes to monitor biodiversity. *Nature Ecology & Evolution*, *7*(9), 1373–1378. https://doi.org/10.1038/s41559-023-02148-z
Sethi, S. S., Jones, N. S., Fulcher, B. D., Picinali, L., Clink, D. J., Klinck, H., Orme, C. D. L., Wrege, P. H., & Ewers, R. M. (2020). Characterizing soundscapes across diverse ecosystems using a universal acoustic feature set. *Proceedings of the National Academy of Sciences of the United States of America*, *117*, 17049–17055.
Sittaro, F., Hutengs, C., Semella, S., & Vohland, M. (2022). A machine learning framework for the classification of Natura 2000 habitat types at large spatial scales using MODIS surface reflectance data. *Remote Sensing*, *14*, 1–20.
Skidmore, A., & Pettorelli, N. (2015). Agree on biodiversity metrics to track from space. *Nature*, *523*, 5–7.
Skidmore, A. K., Coops, N. C., Neinavaz, E., Ali, A., Schaepman, M. E., Paganini, M., Kissling, W. D., Vihervaara, P., Darvishzadeh, R., Feilhauer, H., Fernandez, M., Fernández, N., Gorelick, N., Geijzendorffer, I., Heiden, U., Heurich, M., Hobern, D., Holzwarth, S., Muller-Karger, F. E., … Wingate, V. (2021). Priority list of

biodiversity metrics to observe from space. *Nature Ecology & Evolution*, *5*, 896–906.

Smart, A. S., Weeks, A. R., van Rooyen, A. R., Moore, A., McCarthy, M. A., & Tingley, R. (2016). Assessing the cost-efficiency of environmental DNA sampling. *Methods in Ecology and Evolution*, *7*(11), 1291–1298. https://doi.org/10.1111/2041-210X.12598

Smith, A. C., Harrison, P. A., Pérez Soba, M., Archaux, F., Blicharska, M., Egoh, B. N., Erős, T., Fabrega Domenech, N., György, Á. I., Haines-Young, R., Li, S., Lommelen, E., Meiresonne, L., Miguel Ayala, L., Mononen, L., Simpson, G., Stange, E., Turkelboom, F., Uiterwijk, M., … Wyllie de Echeverria, V. (2017). How natural capital delivers ecosystem services: A typology derived from a systematic review. *Ecosystem Services*, *26*, 111–126.

Smith, P. (2004). Carbon sequestration in croplands: The potential in Europe and the global context. *European Journal of Agronomy*, *20*, 229–236.

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*, 219–241.

Spake, R., Barsoum, N., Newton, A. C., & Doncaster, C. P. (2016). Drivers of the composition and diversity of carabid functional traits in UK coniferous plantations. *Forest Ecology and Management*, *359*, 300–308.

Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., & Strickland, M. S. (2018). What we talk about when we talk about soil health. *Agricultural & Environmental Letters*, *3*, 180033.

Stroud, J., & Bennett, A. (2018). *How to count earthworms* Agriculture and Horticulture Development Board 2. Agricultural & Horticultural Development Board.

UKBMS. (2021). *UK butterfly monitoring scheme*.

UKECN. (2022). *UK environmental change network*.

UKHab Ltd. (2023). *UK habitat classification version 2.0*.

van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T. T., Jongejans, E., Menz, M. H. M., Miraldo, A., Roslin, T., Roy, H. E., Ruczyński, I., Schigel, D., Schäffler, L., Sheard, J. K., Svenningsen, C., Tschan, G. F., Wäldchen, J., … Bowler, D. E. (2022). Emerging technologies revolutionise insect ecology and monitoring. *Trends in Ecology & Evolution*, *37*, 872–885.

Van Klink, R., Sheard, J. K., Høye, T. T., Roslin, T., Do Nascimento, L. A., & Bauer, S. (2024). Towards a toolkit for global insect biodiversity monitoring. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *379*, 20230101.

Waldén, E., Queiroz, C., Plue, J., & Lindborg, R. (2023). Biodiversity mitigates trade-offs among species functional traits underpinning multiple ecosystem services. *Ecology Letters*, *26*, 929–941.

Warner, E., Giuliani, L., Campbell, G., Smith, P., & Smith, A. (2024). *Biodiversity & soil health metrics tool user guide*. Agile Initiativel.

Wauchope, H. S., Amano, T., Geldmann, J., Johnston, A., Simmons, B. I., Sutherland, W. J., & Jones, J. P. G. (2021). Evaluating impact using time-series data. *Trends in Ecology & Evolution*, *36*(3), 196–205. https://doi.org/10.1016/j.tree.2020.11.001

Weiser, E. L., Diffendorfer, J. E., Grundel, R., López-Hoffman, L., Pecoraro, S., Semmens, D., & Thogmartin, W. E. (2019). Balancing sampling intensity against spatial coverage for a community science monitoring programme. *Journal of Applied Ecology*, *56*, 2252–2263.

Wood, E. M., Pidgeon, A. M., Radeloff, V. C., & Keuler, N. S. (2012). Image texture as a remotely sensed measure of vegetation structure. *Remote Sensing of Environment*, *121*, 516–526.

Wurtzebach, Z., & Schultz, C. (2016). Measuring ecological integrity: History, practical applications, and research opportunities. *Bioscience*, *66*, 446–457.

Young, T. P., Petersen, D. A., & Clary, J. J. (2005). The ecology of restoration: Historical links, emerging issues and unexplored realms. *Ecology Letters*, *8*, 662–673.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information Methods S1. Further methodological details, providing full information on how the metrics were chosen and assessed.

Table S1. The selected biodiversity metrics grouped by Tier (Tier 1, Tier 2, Future).

Table S2. The selected soil health metrics grouped by Tier (Tier 1, Tier 2, Future).

Table S3. Summary of standardised methodologies available for collecting data for each biodiversity metric.

Table S4. Summary of standardised methodologies available for collecting data for each soil health metric.

Table S5. A summary of data thresholds or directions of change for each metric indicating a positive outcome for biodiversity.

Table S6. A summary of data thresholds or directions of change for each metric indicating a positive outcome for soil health.

Table S7. A summary of technological innovations that could support biodiversity monitoring in the future.

Table S8. A summary of technological innovations that could support soil health monitoring in the future.

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