LUNZ Hub 15: Aligning soil monitoring, methods and metrics across the 4 Nations

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This project was funded by the Land Use for Net Zero, Nature and People Hub's Agile Policy Centre. The Hub is part of the Transforming Land Use for Net Zero, Nature and People (LUNZ) programme co-funded by UKRI, the Department for the Environment, Food and Rural Affairs (on behalf of England and Wales), the Department for Energy Security and Net Zero, the Department of Agriculture, Environment and Rural Affairs of Northern Ireland, and the Scottish Government.

Executive summary

Rationale for the project

The primary aim of the project was to investigate opportunities for ‘Aligning soil monitoring, methods and metrics across the 4 Nations’ of the United Kingdom. There are many positives to harmonising, sharing and consolidating soil data across the 4 Nations including:

- Advancing scientific understanding of soil systems and soil health, which contributes to more informed, evidence-based decision making
- Potential to improve efficiency with agreed metrics and common guidance provided
- Opportunity for improved transparency and robustness in the collection, use, and interpretation of soil data across sectors
- Fostering long-term commitments to collaboration and innovation into soil health and associated environmental co-benefits

However, data are often collected using different methods for specific purposes, held across different institutions, local authorities and/or countries, and not always in an easy to read/interpret format.

Project components

A core component of the project was a workshop held in June 2025. Representatives from each of the 4 Nations who are either responsible or contribute to soil monitoring were present. Prior to the workshop there was engagement with other stakeholders to gain insight into potential barriers, expectations from a 4 Nations approach, and the importance of soil monitoring alignment to policy. These conversations contributed to forming the topics for discussion at the workshop in June 2025. Workshop activities included the ranking of soil indicators for physical, chemical and biological measures. To aid interpretation of this report, a glossary has been provided at the end of this document.

Key findings on the 4 Nations alignment of metrics/indicator

No current dataset from any of the 4 Nations contained all of the indicators ranked at the workshop considered most important for soil monitoring. Regarding soil chemistry indicators, 6 existing datasets contained all of the top 4 ranked soil chemical indicators. In contrast, there were no existing databases identified that contained all of the biological indicators ranked as important. Similarly, there were no existing single database that had the full breadth of ranked soil physical, biological and chemical health indicators.

Recommended next steps

Policy

- **Challenge**
    - The key challenge is in aligning policy and funding, harmonising data, and achieving agreement and sustained commitment across the 4 Nations

- **Future opportunities and needs**
    - Monitoring outputs should be designed to be useful for policymakers and regulators
    - Prioritise robust trend detection; in parallel, support research to define realistic, land-use- and soil-type-specific thresholds
    - Further work required to understand the resolution requirement for soil monitoring schemes reporting to government
    - Coherent messaging is key to avoid confusion which can sometimes result from information that can appear to be contradictory
    - Subsoil indicators are viewed as a knowledge gap that future monitoring should address

- **Considerations for data sharing and governance**
    - Consolidated soil datasets would provide a useful resource for climate and carbon modelling, inventory reporting, Environmental, Social, and Governance (ESG) reporting, biodiversity assessments, natural capital and wider environmental metrics utilised in policy
    - There is a considerable quantity of soil monitoring data that has already been collected and analysed over the years, yet not all of this is openly accessible
    - A variety of soil sampling methodologies means that ensuring data is shared with sufficient and accurate metadata is essential for aligning and harmonising soil monitoring across the 4 Nations
    - Recommended that a review be carried out of existing datasets to understand the status of data accessibility, based on FAIR principles
    - A key pillar of achieving harmonisation across soil monitoring schemes needs to be consideration of soils data management and governance

Wider landscape of stakeholder needs from soil monitoring

- Through interviews with other stakeholders some suggested alignment by industry/private monitoring with government schemes offering opportunities to leverage private investment to support monitoring
- Leveraging private/industry funding would not be suitable for all and uses highlighting the need for public, policy driven, monitoring also
- Further work required to understand the resolution requirement for soil monitoring schemes reporting to the supply chain and opportunities for alignment to government reporting

- Consolidated soil datasets would provide a useful resource for carbon markets and corporate Environmental, Social, and Governance (ESG) reporting, biodiversity assessments, natural capital and wider environmental metrics utilised in land management decisions

Other project key points for considering national scale soil monitoring:

- **What are the needs for soil monitoring?**
    - Critical to be utilising a common core set of indicators and standards with nation-specific flexibility embedded in law and funding cycles to ensure long-term continuity
    - Not all soil Indicators used for monitoring soils are applicable to all land uses/land cover
    - Embedding soil monitoring in legislation and core government architecture, rather than leave it vulnerable to shifting political priorities
    - The use of “citizen scientists”, to support national scale soil monitoring has gained increasing interest driven by the prominence of soil across a range of policy domains

- **Scientific robustness**
    - Strictly, systematic sampling has the disadvantage that sample variance cannot be estimated properly. However, treating a grid-based sample as though it was a random sample will tend to slightly over-estimate the true sample variance, meaning that confidence intervals will tend to be slightly wider than necessary but safe to use

- **Key indicators for monitoring soils**
    - Agreement on what core indicators should be considered for monitoring soil physical, biological and chemical status
    - No single indicator set can cover all soil functions and that cost, feasibility and interpretability must be considered
    - Beyond indicators selected, additional indicators may be derived from associated measures, or through the inclusion of new indicators such as metabarcoding and eDNA however multiple challenges exist, such as data storage and baselining

- **Integrating data sources**
    - Different soil measurement methods vary in both the accuracy and the precision of the soil property that is being measured with a need for methodologies to be made available along with the raw data to account for methodological differences
    - Soil sampling not undertaken as part of a structured survey has a greater risk of bias
    - Different data sources can come with different usability and licensing constraints

- **Soil archive**
    - An archive, either within each nation or a single UK wide archive, would allow later analysis when a specific environmental, public or animal health issue arises in the future
    - Archived samples can be used to determine new and novel soil properties using techniques that weren’t available at the time of sampling
    - For a monitoring scheme, it is important to not only compare data overtime but to have the capacity to re-run the analyses if instruments or procedures change
    - It is critical to archive sufficient material to re-analyse the sample a number of times at each successive sampling campaign
    - Soil sample storage and archiving is also essential to the monitoring of existing and emerging threats to soil health

Introduction

It is increasingly being acknowledged beyond the soils research community of the value in soil health the need to monitor soil degradation, and the need for harmonising/aligning these data. Soil data is valued for reporting against specific policy or industry need however the value of monitoring all aspects of soil health, beyond specific policies, requires support with a coordinated approach across the 4 Nations. Challenges associated with the assessment of soil health can be associated to some degree by soils falling within multiple policy areas resulting in fragmented monitoring and the use of multiple indicators and sampling strategies. The data collected to date has significant value but there is a need to understand whether a ‘harmonised’ or ‘aligned ‘approach should now be put in place to monitor changes in soil health. Fundamental to the wider question is ‘what’ should be measured, ‘where’ alignment on these measures are in existing datasets, and ‘where’ there could be improved alignment.

The primary aim of the project was to investigate opportunities for ‘Aligning soil monitoring, methods and metrics across the 4 Nations of the United Kingdom. Differentiation of the terms ‘alignment’ and ‘harmonisation’ are critical to understand in the context of this project and may be simplified as follows:

- **Alignment:** Agreement on a direction of travel with the same measure being collected to monitor potential change, however, the specific methodologies in each Nation may vary. Alignment would accommodate local variations in methodology, but this then presents challenges in terms of national reporting and inventory requirements for soil health. One example where this approach may not be appropriate might be where Soil Organic Matter (SOM) is measured by Loss On Ignition (LOI) where ignition temperatures are different. Conversely, the measurement of soil phosphorus (P) is influenced by soil pH’s and different methods are adopted in Scotland to those in England (modified Morgan’s v Olsen P) to account for the greater proportion of alkaline soils on the chalky drifts in England.

- **Harmonisation:** In contrast to alignment, ‘harmonisation’ would be the collection of measures utilising the same methodologies and protocols allowing direct comparison rather than the broader direction of change in each Nation. The advantage of this is that it would facilitate spatial and temporal comparisons of soil attributes across the UK, allowing for an overall assessment of UK soil health. The disadvantage is that harmonisation of sampling and analysis methodology is not suitable for all metrics (see measures of soil P above). To fully understand the challenges in taking one approach over another, a full exploration of this for each metric would need to be undertaken. One key risk would be in losing the ability to hindcast change based on previously collected data which had not been analysed using the same approaches, methods, or protocols.

Core to the delivery of the project was a workshop to understand key challenges and identify core indicators which should be monitored within a future UK wide (4 Nations) monitoring scheme. The workshop took place in June 2025 with representatives from key government and stakeholder agencies from each Nation. From the very beginning it was noted that there was a considerable body of work starting in 2002, that provided a valuable resource in understanding the evolution of discussion on the topic.

Outputs from the workshop have been included in this report with 3 key soil indicators proposed for each of the physical, biological and chemical components of soil. The workshop also highlighted the opportunities in designing a future monitoring system with recommendations on approaches which may alleviate some of the perceived challenges. The timing of this report cannot be over emphasised with an opportunity to support the development of soil monitoring within at least 2 of the Nations with devolved powers, Scotland and Northern Ireland. Northern Ireland is coming to the end of the Soil Nutrient Health Scheme and is looking at what might follow on from this with the inclusion of metrics beyond chemical measures. Scotland is also developing a soil monitoring framework based on outputs of the Strategic Research Programme (2022-2027) and understanding the value of the National Soil Inventory of Scotland (NSIS) data in supporting this.

It is important to acknowledge the current context of the work performed as part of this project. In Europe, projects such as EJP Soils, in which only Northern Ireland was eligible to participate due to Brexit, aimed to develop knowledge and data bases to improve the European contribution towards international reporting on soil status and improve the impact of European agricultural policies on soil health. This is also to support the adoption of the Soil Resilience and Monitoring Law. Within EJP Soil, there is a requirement for some degree of harmonisation in soil monitoring so that data flows can be streamlined. Streamlining data flow would support the development of thematic databases and maps of soil properties and management systems, potentially enabling target values of agricultural Soil Organic Carbon (SOC) to be set, along with other indicators of fertility and of degradation. In the future, a Soil Innovation Partnership is being launched, based on a multi-funder model with farmers and landowners very much central to this due to a living lab approach being favoured. These living labs are collaborations between multiple stakeholders at a regional scale where experiments can be undertaken under real-life conditions. Living labs are not just focussed on cultivated land but can also encompass uplands and forests, landscapes and land uses that are often overlooked.

Participants in the food supply chain are also becoming increasingly interested in soil health and are supporting change through individual soil monitoring support (including Arla, Danone, M&S, First Milk, Sainsbury’s and Diageo) and involvement in broader Living Lab approaches (such as through the Landscape Enterprise Networks (LENs)). With significant and complementary interest across a broad stakeholder grouping, there is potential opportunity to work together to deliver a meaningful approach to soil monitoring. However, this will require an understanding of the needs of different sectors. The adoption of key soil metrics to be collected in all sampling schemes may open opportunities to work more closely across multiple sectors in the future.

In order to discuss these aspects more fully, the report has been split into 8 sections:

- What are the needs for soil monitoring at a national scale?
- Key indicators for soil monitoring
- Indicators aligned and harmonised in existing dataset
- Integrating data sources
- Value of a soil archive
- Data sharing and governance
- Future opportunity and needs
- Challenges

1. What are the needs for soil monitoring at a national scale?

National scale soil monitoring is important for identifying broad-scale trends at a national level that pose a risk to soil health, which may for example be driven by climate or land use change or broad scale land management. Different approaches to monitoring may be appropriate for different soil types and land uses, but while the proportions of these vary regionally, differences do not follow administrative borders.

One of the initial actions prior to the June workshop was to interview several key stakeholders to understand areas of common agreement and those areas where opinions were more divided. Outputs from each of these interviews were collated with an outline below of the key findings.

Strong agreement

1. **Need for a 4 Nations, harmonised soil monitoring framework**
    - Consistent methods should be applied where feasible, with a **framework to reconcile differences** (e.g., interoperability tables)
2. **Monitoring must outlast individual policies**
    - Policies are changeable whereas **soil monitoring should be long-term, stable, and fundamental** incorporating an ability to report into evolving policy frameworks
3. **Barriers are largely institutional and financial, not scientific**
    - Short-term funding, policy volatility, lack of leadership, competition, data ownership, and weak engagement between communities were highlighted as areas where barriers may exist
4. **Stratification and indicator selection must be both driven by the question and the function being monitored**
    - Challenges in taking a '*one-size-fits-all*' approach; acknowledgement of multiple strata (e.g., soil type, land use, climate, etc.); an initial 'grid' based approach would allow 'stratification' of soil type and land use to be applied later. However, stratification may be required depending on the questions asked by monitoring; monitoring may require a mix of universal and land-use-specific indicators
5. **Importance of interpretation, communication, and trust**
    - Soil data must be interpretable (what does a number mean for soil health?) and easily communicated to a range of stakeholders including farmers, industry and policy makers

Key opinions and tensions

1. **Technical vs social focus**
    - Some of those interviewed felt that a future framework should be more focussed on a technical and methodological approach
    - Others acknowledged that societal and industry indicators should be standardised for inclusion in a monitoring framework

2. **Difference of opinion on universal indicators**
    - **Some stakeholders felt that a small, clear, core set** (with Soil Organic Matter (SOM) as the lead) was required with others more cautious, stressing that **different landscapes require different indicators**, and some common agronomic measures would not be suitable for all land uses or cover
    - **It was acknowledged that some users of data apply the results in different ways. Modelling may require a different universal measure for model inputs**, not necessarily the same headline indicators
3. **Stratification emphasis**
    - Grouping by soil type allows simpler communication
    - Stratification should be based on inherent, non-changeable, properties with stratified random sampling
    - Stratification can be driven by a mix of factors which may be context-dependent
4. **Relationship to industry and private schemes**
    - Some of those interviewed placed a strong emphasis on aligning industry/private monitoring with government schemes with opportunities to leverage private investment in supporting monitoring
    - Not all land-use will be suitable for funding monitoring through industry and private funding highlighting the need for public, policy driven, monitoring

Outcomes from stakeholder interviews supported the development of the workshop which took place in June 2025. In the broadest sense, there was strong support for a 4 Nations) soil monitoring framework that treats soil as a cross-border, multi-functional national asset, underpinning many policy areas (including climate, water, biodiversity, food security, public health). Furthermore, it is critical to be **utilising a common core set of indicators and standards with nation-specific flexibility and that this should be embedded in law and across funding cycles to ensure long-term continuity**. Soil-related issues and drivers (e.g., water quality, flooding, air pollution, greenhouse gases, food security, cross-border catchments) were transboundary with similar policy frameworks across the 4 Nations creating an opportunity for a UK-level scheme that improves comparability, supports national and international reporting, and provides a system-level perspective on both soil and ecosystem health.

However, policies aimed at improving soil health, such as those associated with the Scottish agricultural reform programme, are devolved issues. To measure the effectiveness of measures, national monitoring could be supplemented by targeted sampling to examine the impact of management in each of the 4 Nations. It is important that this includes the collection of metadata such as the location of samples and the sampling and analysis methods used. Practical and political challenges, including differences in current schemes and methods, variable capacity to sample soils and issues around soil literacy, data licensing barriers, and the risk that an overly narrow indicator set, or single policy driver, and costs to deliver such a scheme, may constrain the system in the future.

Comments made through interviews and at the workshop highlighted that there was a **strong desire from those involved in government and stakeholder organisations to embed soil monitoring in legislation and core government architecture, rather than leave it vulnerable to shifting political priorities.** A 4 Nations scheme is seen as adding resilience: it is more difficult for one nation to quietly drop out.

Broadening soil data beyond the United Kingdom, there are a multitude of short-term (typically 2-4 years in duration) datasets of soil characteristics (biological, chemical, and physical) associated with individual European Research and Innovation Actions. Structured soil monitoring across Europe is mostly limited to the Land Use/Cover Area frame statistical Survey (LUCAS), originally established in 2009. Moreover, these short-term datasets are rarely interoperable, and harmonisation of methods is scarce.

In contrast to the individual Research and Innovation Actions, LUCAS is a regular soil survey (typically every 3 or 4 years) across all EU Member States (including the UK up to2018) using harmonised methodologies to gather information on land cover, land use and a range of soil characteristics.

Since 2022, The Soil Biodiversity Observation Network (SoilBON) has established harmonized protocols and sampling strategies to monitor soil biodiversity and soil ecosystem functions and their change over time in nature conservation and non-conservation areas (> 500 sites) alike across Europe and beyond with an ambition to sample sites every 3 years.

Going forward, it is the ambition of the EU Mission: A Soil Deal for Europe to establish a network of 100 Living Labs and Lighthouses in rural and urban areas by 2030 to support the transition towards healthy European soils. Using harmonised methods aligned with EU policy instruments, it is envisaged that Living Labs and Lighthouses will have a key role in accelerating the adoption of sustainable practices by practitioners and fostering the development of solutions tailored to specific local conditions. **Such examples from Europe highlight the potential for the UK to fall behind with national level reporting, despite having numerous datasets (as highlighted at a workshop held in February 2024 in London and organised through the LUNZ hub) which must be brought together within a single system in the future**.

How far apart are we technically?

Differences in soil sampling methods as well as analytical methods can limit comparability between the 4 Nations. The National Soil Inventory of Scotland has compared three different sampling methods: sampling by pedogenic horizons, a single 0-15cm core, and a composite of 0-15cm auger samples. A comparison between a single ‘point’ sample and a composite sample over a wider area (**Figure 1**) showed that although results were similar for cultivated soils, there can be considerable differences between measurements from samples collected using different methods from organo-mineral and organic soils, affecting soils under moorland and woodland in particular. This is partly, but not entirely, due to short-range variability in upland, semi-natural, soils and that the composite samples contained soil from more than one contrasting horizon. Thus, differences in sampling methods may affect not only mean values but also variances. Taking multiple samples or a composite sample at each site will reduce the effect of local spatial variation, reducing the uncertainty in estimated mean values and trends. It should be noted that this is only associated with site level monitoring with spatial variation at a national level averaged out across samples.

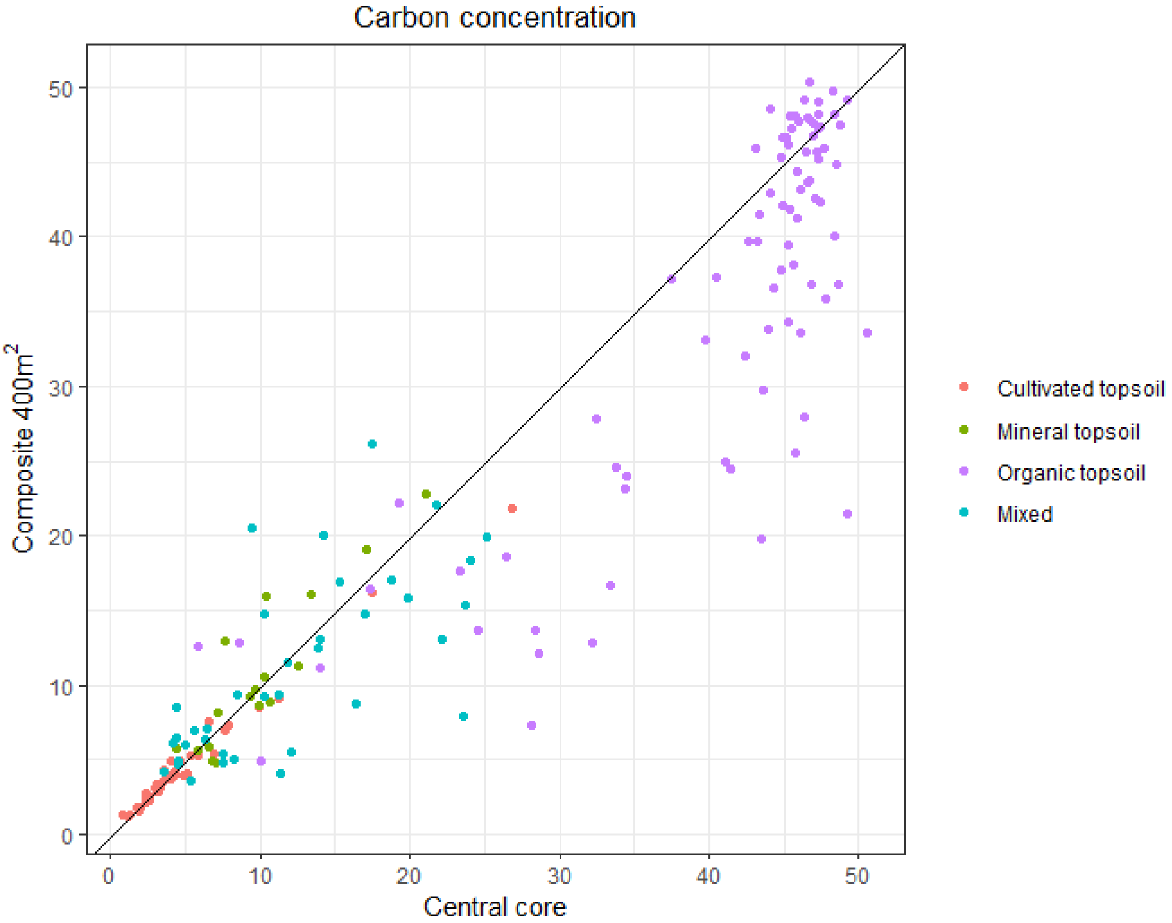

Figure 1. Soil organic carbon concentrations as measured from intact 15cm deep cores from the soil surface of a soil profile pit or from composite 0-15cm auger samples from a 400m^2 area centred on the soil pit. There is significant variability in relationship between C concentrations depending on whether the sample was taken from a soil that was cultivated, had a mineral or an organic topsoil, or comprised a mixture of organic and mineral layers within 15cm from the soil surface.

Differences in overall sampling design should not affect the estimation of overall means and trends but can affect the uncertainty with which these are estimated. Most monitoring schemes use either a regular grid or stratified random sampling approach, or some combination of these Stratified random sampling divides the population into non-overlapping categories (strata) and randomly samples from each stratum in proportion to the stratum's size, which can lead to greater precision for a given sample size than completely random sampling. Stratified random sampling has the advantage that it is possible for the sample sizes to be varied disproportionately to the areas of the strata, allowing these to be adjusted to ensure adequate sample size in each reporting class. If this is done, then the data needs to be weighted in inverse proportion to the probability of each site being included in the sample. In contrast, grid-based sampling ensures even coverage of an area, which can also lead to potentially greater logistical efficiency however, efficiency within a random stratified approach may be achieved due to increased application of GPS technologies. Strictly, systematic sampling has the disadvantage that the sample variance cannot be estimated properly. However, treating a grid-based sample as though it was a random sample will tend to slightly over-estimate the true sample variance, meaning that confidence intervals will tend to be slightly wider than necessary but safe to use (the precautionary principle).

For specific land-use/cover, for example forestry soil, monitoring needs to account for the differences in soil development under these different ecosystems. In terms of forestry, sSuch monitoring must acknowledge important differences, such as:

- good soil structure (as less disturbed compared to more intensively managed soils, such as arable soils)
- more acidic (due to acidic inputs by trees)
- high organic matter and humus layer accumulations
- tree root influence on surface but also deeper within soils

Indicators used for monitoring soils under different land use can differ therefore the protocols need to encompass all soil types and all land covers/uses. For example, harmonisation of protocols was achieved under DEFRA tNCEA BioSoil and EES soil surveys, but additional indicators, methods and assessments needed to be included for forest soils to capture the difference in properties and functions. The National Soil Inventory of Scotland sampling protocols (Lilly *et al*., 2011) were also created to encompass lowland cultivated soils as well as soils in the uplands and soils under forests. However, there are additional soil indicators that are especially used / emphasised in forest protocols that may not be included in the more holistic sampling schemes for upland land covers. **Table 1** highlights those indicators specific to forested soils and those that are also relevant to upland semi-natural soils. Much of upland UK has peat or organo-mineral soils under a semi-natural vegetation (such as heather moorland) as well as land under forestry though mineral soils do also occur. The organo-mineral and peat soils will differ in the relevant indicators compared to cultivated, lowland soils (**Table 2**).

Table 1. Indicators used within forest soils highlighting their relevance and application to semi-natural upland soils. Text box colour indicates relevant to both soils under forestry and those under semi-natural vegetation and recorded in semi-natural soils 🟧; relevant to mainly soils under forestry but potentially relevant to soils under open, upland semi-natural habitats 🟦; no equivalent indicator for soils under semi-natural vegetation 🟥.

Specific forest soils indicators	**Comments**
Surface organic layers	
Organic matter thickness (Litter, fermentation and humified layers	As C concentration generally stays constant, changes in C stocks needs to take account of changes in thickness. Detecting change in peat soils is difficult if depth exceeds around 1.2m due to difficulty in sampling for C and bulk density at depth. Generally, not found in cultivated soils
Dry mass per area of the organic layer (t/ha)	Needs C concentration and bulk density
C and N stocks (t C or N/ha)	Needs carbon & nitrogen concentration and bulk density
Humus form / humus type (e.g., mor, moder, mull)	Indicator of soil and climatic interactions, often part of the profile description
Degree of decomposition of organic horizons (e.g., using von Post scale)	Von Post classification is increasingly used but also categories such as amorphous, semi-fibrous and fibrous are commonly used to indicate degree of composition
Acidification / acid-base status	
Exchangeable Al^{3+} and H^+	Often described as exchangeable acidity
Al saturation (% of effective CEC occupied by Al)	Not a standard measurement in soils in semi-natural, upland, and open habitats
Base saturation of the *effective* CEC at actual soil pH	Often calculated for upland soils by extraction of base cations
Non-exchangeable / adsorbed sulphate (SO_4^{2-})	In some acid-deposition studies for forest soils and specific research projects or upland soils
Acid neutralising capacity (ANC) / base cation surplus	Can be calculated from proportion of exchangeable base cations in semi-natural soils
Profile-level nutrient reserves and weathering indicators	
Total Ca, Mg, K, Na stocks (kg/ha) in the full profile	Generally measured to 1m or 1.2 m depth or to rock.
Weathering index / nutrient sustainability indices	Nutrient removals vs weathering supply, often based on total element contents in specific horizons

Organic matter quality indicators	
C:N ratio of organic and mineral layers	Standard measure across all soils
Lignin or polyphenol proxies in the organic layer	Using specific indices or near-IR–based quality indicators
Humus form classification	As above
Soil solution / leachate chemistry	
DOC, nitrate, ammonium, sulphate, chloride, base cations in lysimeter soil solution	Soil solution chemistry is mostly a **research / monitoring tool** and is more common in forest acidification and deposition studies than in routine soil testing
Al and heavy metals in solution	Soil solution chemistry is mostly a **research / monitoring tool** and is more common in forest acidification and deposition studies than in routine soil testing
Root zone and coarse-root related indicators	
Rooting depth	Presence of hardpans, dense horizons, waterlogging, or bedrock that restrict root penetration are generally recorded in profile descriptions but of more relevance to deeper rooting trees
Coarse root abundance / root distribution by depth	Root size, frequency and type generally in recoded profile descriptions.
Evidence of windthrow susceptibility related to soil/rooting conditions	Land Capability for Forestry assessment on site
Stand–soil interaction indicators (qualitative)	
Species-specific nutrient deficiency / toxicity indicators inferred from soil + foliage + humus	Forestry specific
Podzolisation / gleying status and depth	Standard soil profile classification provides context to soil functions. Some podzolic horizons can be toxic to plants

In addition to the indicators relevant to forestry, indicators for upland, open semi-natural habitats include bacteria, archaea, fungal and nematode diversity (DNA methods) and erosion features which are of relevance to peatlands (Neilson *et al*., 2021). The depth to saturation in peat soils is key indicator for both carbon sequestration/loss and GHG emission.

Table 2. Comparison of high-level indicators mainly relevant to soils under forestry but potentially relevant to soils under open, upland semi-natural habitats in Table 1.

Forestry	Crop and grassland
Forest floor (Organic horizon–specific indicators	Generally, not present in cultivated soils
Acidification / acid-base status	Focus generally on available plant nutrients and pH status, though acidification can be a feature of cultivated land
Profile-level nutrient reserves and weathering indicators	In cropland, tests usually focus on plant-available P, K, Mg and often focus on the top 10–20 cm for fertilizer decisions, however, total reserves over the whole profile are a key part of soil survey characterisation
Organic matter quality indicators	Most cultivated soils have a mull topsoil
Soil solution / leachate chemistry	Mostly a research tool in both forestry and cultivated land rather than a monitoring tool
Root zone and coarse-root related indicators	Rooting is constrained by the same factors in both though may be more relevant for deep rooting trees
Stand–soil interaction indicators (qualitative)	Partially relevant to cultivated soils that are *podzolic* or *stagnic*. *Podzolic* soils have poor nutrient retention and *stagnic* soils become waterlogged readily

Potential for citizen science to contribute

The use of “citizen scientists”, i.e., a member of a cohort such as the public who participate in scientific research, **to support national scale soil monitoring has gained increasing interest driven by the prominence of soil across a range of policy domains.** This has arguably been led by the European Union who, for over a decade, have funded citizen science projects focussed on soils such as the Grow Observatory and ECHO. Moreover, increasing citizen engagement is an objective of the EU Mission: A Soil Deal for Europe to support policies such as the EU Soil Strategy for 2030, the Nature Restoration Law and the recently adopted EU Soil Monitoring Law.

To date, citizen soil science activities fall into three discrete areas namely, collecting data for monitoring, increasing soil literacy of participants and data generated facilitating downstream decision-making. However, soil-related citizen science is considerably less mature than equivalent citizen science activities associated with biodiversity or water research such as (invasive) species or pollution monitoring.

It is recognised that citizen science monitoring can significantly increase both the volume and resolution (in terms of spatial granularity) of soil data, particularly for soil characteristics such as organic carbon content, nutrient levels, and pollutant concentrations which do not necessarily require intricate sampling protocols. It can also be used to access hard to reach locations, as demonstrated in a study to assess alpine soil biodiversity on mountains in Scotland. However, it is **also acknowledged that there are challenges associated with citizen science derived (soil) data including data quality, inconsistencies with data validation, citizen scientist attrition which hinders repeatability and dilutes the knowledge pool, digital literacy (many citizen science projects depend on mobile devices) and data privacy including data ownership.**

To address these challenges and potential barriers in-keeping with the global soil community there are significant efforts to standardize protocols to harmonize citizen science data collection, while at the same time integrate remote sensing and sensor-based validation methods, to improve the reliability of citizen science generated data.

Key points

- **Critical to utilise a common core set of indicators and standards with nation-specific flexibility embedded in law and across funding cycles to ensure long-term continuity**
- **Indicators for monitoring soils under different land uses can differ**
- **Embed soil monitoring in legislation and core government architecture, rather than leave it vulnerable to shifting political priorities**
- **Potential for the UK to fall behind with national level reporting, despite having numerous datasets which must be brought together within a single system in the future**
- **Sampling locations should be chosen using a scheme that is designed to be representative, such as a stratified random sampling scheme or a systematic grid.**
- **The use of “citizen scientists”, to support national scale soil monitoring has gained increasing interest driven by the prominence of soil across a range of policy domains**
- **Recognised challenges associated with citizen science derived (soil) data including data quality, inconsistencies with data validation, citizen scientist attrition which hinders repeatability and dilutes the knowledge pool, digital literacy (many citizen science projects depend on mobile devices) and data privacy including data ownership**

2. Key indicators for monitoring soils

One of the key requirements in the development of an aligned or harmonised 4 Nations approach to soil monitoring is agreement on the key soil metrics and indicators to be assessed. Since 2002 and the publication of 'Identification and development of a set of national soil indicators for soil quality', multiple projects have investigated key indicators, an overview of these has been provided in **Appendix 1, 2, 3, and 4**. The June workshop offered an opportunity for key stakeholders and government agencies to broadly discuss these and select which indicators could potentially be adopted to monitor soils, incorporating the three core aspects of soil health: biological, chemical, and physical status.

The indicators which were voted on for inclusion in soil monitoring were collated from the multiple published works to date and were not intended to be exhaustive but provided a baseline for discussion. Within the event workshop, attendees also had the opportunity to highlight any indicators which were missing and should be considered for potential inclusion. Costs associated with each measure were not included to avoid potential bias in the value of each indicator.

Participants broadly agreed that the proposed set of core soil health indicators (**Table 3**) was a strong starting point, particularly for physical and chemical properties. Of 18 indicators proposed (6 physical, 5 biological, and 7 chemical) there were clear preferences with bulk density, microbial communities, and topsoil SOC the preferred indicator in each of the 3 categories (**Figure 2**).

However, there was discussion around the merit for expanding the list provided to include key nutrients (especially phosphorus and nitrogen, potassium and base cations), a broader set of contaminants (heavy metals, "forever chemicals", microplastics, hydrocarbons), and more biological and faunal indicators (e.g., earthworms, nematodes, microbial community metrics, eDNA) were also proposed and discussed. The list of indicators highlighted as missing may be found in **Table 4 which includes responses from the project team on their potential for future inclusion (Table 5).** Highlighted in these indicator discussions was acknowledgement that **no single indicator set can cover all soil functions and that cost, feasibility and interpretability must be considered**. For example, via tiered analysis, careful distinction between contextual, practice, and outcome-based indicators, and investment in archives and 'harmonised' methods.

Table 3. Soil indicators highlighted discussed at the June 2025 workshop in Birmingham which were subsequently ranked by attendees for inclusion within a 4 Nations soil monitoring framework

PHYSICAL	BIOLOGICAL	CHEMICAL
Bulk density	Microbial community structure/ biomass	Topsoil soil organic carbon (SOC) (%)
Water retention characteristics	Potential (multiple) enzyme activities	Soil pH
Water content	Nematode community structure	Carbon:Clay ratio
Depth of soil/ topsoil/ rooting depth	Microarthropod community structure	C:N ratio
Topsoil aggregate stability	Respiration/ biomass (qCO_2)	Base saturation
Packing density		Total Zn, Ni, Cu, Cr
		Cation exchange capacity (CEC)

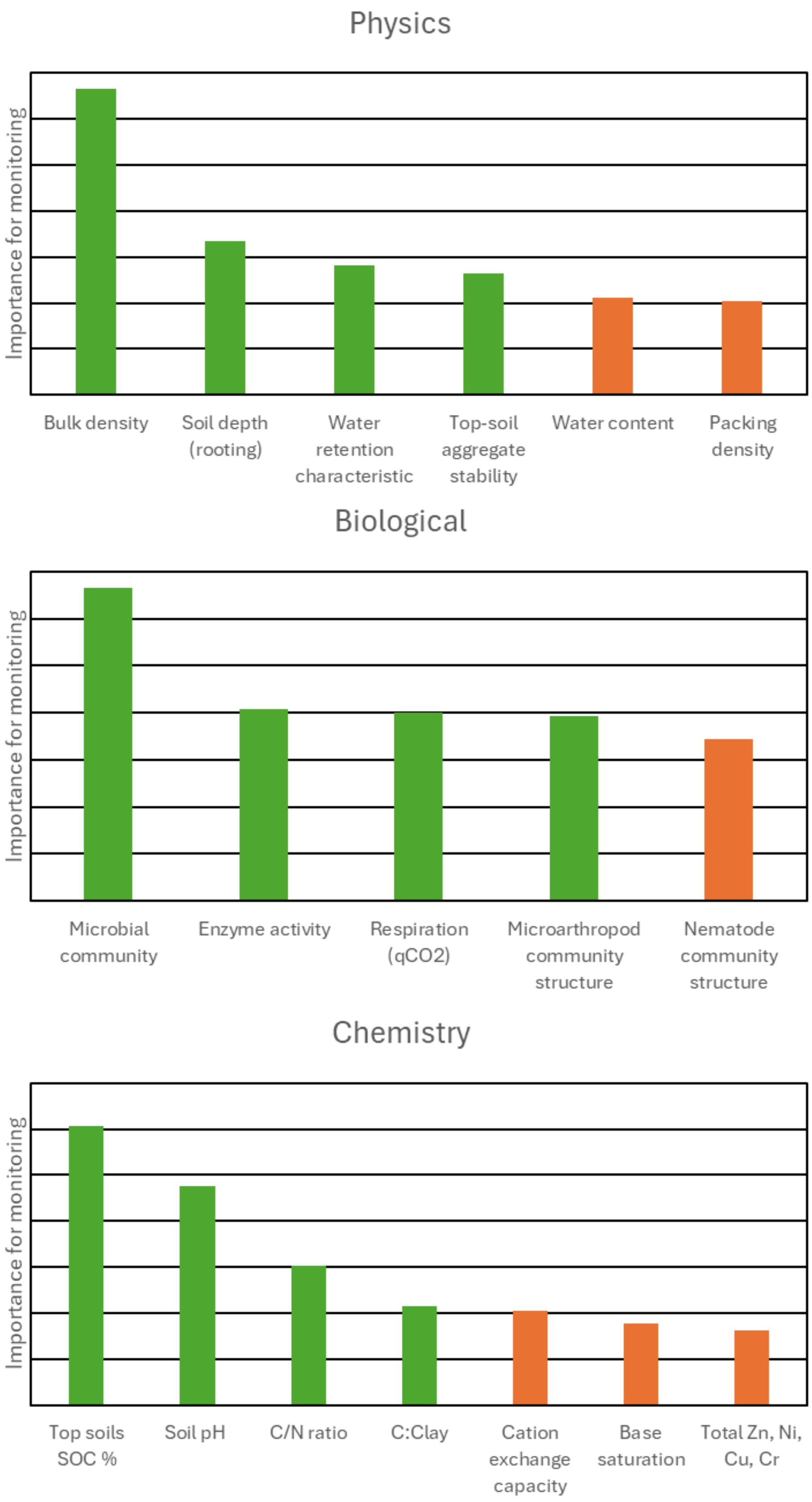

Figure 2. Soil health indicator ranks for physical, biological and chemical components of soil health, top 4 indicators highlighted in ‘green’ following scoring at the June workshop attended by 4 Nation government and regulator representatives with responsibility for soils

Table 4. Soil indicators highlighted as ‘missing’ in those proposed at the workshop

PHYSICAL	BIOLOGICAL	CHEMICAL
Stone content	Earthworms (including abundance/diversity)	Macronutrients (N, P, K, Mg, Ca, S)
Soil depth	Plants / Plant diversity	Nutrients (general, available N, ammonia & nitrate, available P, total P)
Soil structure (e.g., VESS)	Root biomass	Carbonate
Pore size distribution	eDNA / Metabarcoding / bio-eDNA / PLFA	Different carbon fractions (hot water extractable C, labile C, soil C pools, carbon stocks)
Subsoil indicator	N mineralisation potential	Heavy metals (fuller suite, Zn, Ni, Cu, Cr)
Contextual information (soil type	Pathogens	Forever chemicals/contaminants (PFAS, microplastics, emerging contaminants)
Mineral clay	Microarthropods (if mentioned separately)	Phosphorus (available and total)

Table 5. Soil indicators highlighted as ‘missing’ and commentary from project members

PHYSICS	NOTES ON SUGGESTION
Stone content	Useful indicator and required to quantify soil carbon stocks and soil nutrient stocks. Stone content will also influence soil hydraulic characteristics including water holding capacity and conductivity. Stone content is also required should water release characteristics, which was ranked third as an indicator for soil physics at the June workshop, be measured. Within the workshop, soil bulk density was ranked as the top indicator which would be reported as ‘fine earth’ bulk density which excludes stones so it could be argued that stone content would be known through the quantification of bulk density. However, where soil has stones larger than bulk density sampling rings, the volume of all stones needs to be measured or, more likely, estimated to correct any stock measurements.
Depth to water table	Essentially depth to a saturated zone, this is highly relevant for peatland assessments.
Visual Evaluation of Soil Structure (VESS)	Soil structure would be characterised to some degree using water stable aggregates as an indicator, ranked fourth in the list of six soil physics indicators. A better indicator of soil structure would be water retention characteristics from which pore sizes can be inferred and indicate connectivity and drainage. Aggregate stability is a truer measure of structure however this is contested with some viewing this as an indication of potential resistance to erosion and other characteristics such as air-filled porosity. VESS is an option to characterise soil structure with caution in its use due to potential user subjectivity. Several studies have highlighted VESS sensitivity to soil quality indices.

Pore size distribution	Water retention characteristics were ranked third in the list of indicators considered within a 4 Nations approach to soil monitoring. Should this be adopted, pore size distribution data would be potentially available through extrapolation of pore drainage size classes associated with specific water potentials. Alternative methods could also be the implementation of saturated hydraulic conductivity, compaction via air capacity /drainable porosity measurements as well as water holding capacity (required for reporting within the EU Soil Monitoring and Resilience Law). It should be noted that hydraulic conductivity measurements would only characterise the distribution of pores that are connected, not total which includes pores that are not connected, CT imaging methods are an alternative to do this.
Subsoils	Some measure of subsoil would be very helpful, and this may be accounted for when investigating sampling methodology or horizon v depth. Depth to subsoil may be a crucial measure in organo-mineral soils where C concentration would remain largely the same while depth/thickness could change (due to erosion for example) indicating either an increase or decrease in C stock. It is also suitable for cultivated soils where deeper ploughing can simultaneously increase the topsoil thickness and dilute the C concentration by incorporating subsoils that have inherently lesser C content. The National Soil Inventory of Scotland showed a decrease in C concentration in cultivated topsoils but an increase in topsoil thickness leading to no significant change in C stock.
Contextual information (soil type)	The would be included in baseline sampling that would not need to be recorded at the same temporal variability as other indicators. Strongly suggest that this measure is included but not necessarily an intrinsic indicator.
Mineral clay	Clays as a mineral will not change over short timescales however it is acknowledged that this measure may be useful for forestry with exchangeable cations potentially a surrogate for forestry need. It is important to acknowledge that mineral clay and clay as a particle size is different. Clay (defined as a particle size) is used in EU Soil Monitoring and Resilience Law in relation to carbon concentrations to normalise critical carbon concentrations and to establish a soil ‘quality’ indicator, e.g., the ratio of carbon to clay, an indicator with published thresholds.

BIOLOGICAL	NOTES ON SUGGESTION
Earthworms (including abundance/diversity)	Earthworms are a useful indicator BUT not as an abundance (biomass) measure only as this does not provide any information on functional diversity. Given the few people in the UK that can identify earthworms to species, a DNA approach is required. However, it should be noted that earthworms are cryptic, that is, different species look similar which can cause some (minor) issues. However, earthworms may be a useable indicator in all land cover types, e.g., peatlands. It may also be inadvisable to compare earthworm data across land use types. For example, there are fewer earthworms by default in forest soils than grassland soils, therefore such a comparison is not appropriate. However, within land use types, data would be a good comparator. Note that under Scottish conditions pH was considered a limiting factor for earthworm presence in a national survey incorporating cereal and grassland fields (Boag *et al*., 1997) but the literature does suggest that a very rough rule of thumb, pH < 4.5 becomes increasingly limiting for earthworms.
Plants / Plant diversity	There may be opportunity to understand further how aboveground diversity represents belowground “soil health” in intensively managed soils. There is evidence that this may be possible in semi-natural and forest ecosystems.
Root biomass	Root biomass would not be a good indicator as this can change by plant cultivar/variety/species, pathogen burden and soil structure.
N mineralisation potential	The measure relates to quantifying the fraction of organic N which may been converted to mineral N under certain conditions. The ratio of mineralisable N to organic N reflects potential N available to plants.
Pathogens	Valuable in terms of assessing soil health in terms of pathogen burden. Assuming a DNA approach, data can be generated in two ways: a) targeting specific pathogens using species (or strain) specific primer sets and/or b) discovery through metabarcoding/eDNA approaches.
Microarthropods (if mentioned separately)	Potentially but, in a similar way to nematodes, the constraint will be having an expertise pool available to identify the taxa to function. As with all biological indicators, abundance and/or biomass is an inappropriate measure without functional information.

eDNA	A label that is arguably mis-used more often than “soil health” is eDNA. In the simplest terms, eDNA in its current form applied to soil is metabarcoding repeated for multiple taxa across as many Kingdoms as possible. Currently, there is no single universal primer set for soil that operates across all Kingdoms/phyla, therefore several metabarcoding runs are required to capture as many phyla/Kingdoms as possible. Whereas metabarcoding, as described previously, could, for example, focus on a single taxon, such as nematodes, eDNA would generate data on bacteria, fungi, nematodes, mites, earthworms, collembola, arachnids, etc. The approach however requires experts to align generated data with function with similar downsides to those mentioned for metabarcoding. An additional point of note is that there would be a key need requiring capacity to process/store/analyse terabytes (and now petabytes) of data.
Metabarcoding/PFLA	PFLA is “cheap and dirty” but will yield functional information and relative proportion data but limited primarily to bacteria and fungi. Crucially, it will not provide information on diversity. Metabarcoding is arguably now the default methodology for taxa specific analysis yielding relative abundance data that post downstream analysis will yield info an alpha and beta diversity, though not functional diversity. Two things are crucial to the success of using metabarcoding: i) a robust universal primer set and ii) a curated sequence database to match taxonomy. Generation of a taxonomy table can then be used by experts to assign function. Robust universal primers and curated datasets for bacteria, fungi and nematodes are well characterised. However, without such robust molecular markers or a curated database, results will have a lower confidence, especially if public sequence repositories are used to support taxonomic assessment. The downsides of these approaches include that different sequencing platforms yield datasets at different taxonomic resolutions, and that the technology is moving so fast that protocols/chemistries are in constant flux This, therefore, requires an expert in the taxon being studied to match sequence data to functional diversity. Too many unscrupulous actors offer “DNA services” through applying methodologies from the plant kingdom which do not readily transfer to soil. Currently, so-called “short read” methods are the default, in a few years’ time, or sooner, “long read” methods will be the default which generate more sequence data.
Metagenomics	Slowly gaining traction due to costs reducing. This methodology will potentially be the likely endpoint of DNA-based monitoring as functional data can be generated or inferred.

Key points

- **Agreement at the workshop on what core indicators should be considered for monitoring soil physical, biological and chemical status**
- **No single indicator set can cover all soil functions, even those selected at the workshop, and that cost, feasibility and interpretability must be considered Beyond indicators selected, additional indicators may be derived from associated measures, or through the inclusion of new indicators such as metabarcoding and eDNA however multiple challenges exist, such as data storage**

3. Indicators aligned and harmonised in existing datasets

A workshop in London (February 2024) collated information from 16 datasets from each of the 4 Nations. These ranged from UK wide assessments to more local assessments and studies addressing specific questions, such as the impact of afforestation.

To align these data and use them together across the 4 Nations there needs to be a consideration of the questions being addressed, the spatial coverage and statistical design of the sampling schemes, the field sampling methods and laboratory analysis techniques. An assessment of 9 key datasets available at national, or UK scales has been outlined in **Appendices 2** with key indicators identified in the Birmingham workshop (June 2025) cross referenced to the London workshop datasets (February 2024) (**Appendices 3, 4 and 5**).

Within national or UK level datasets, a number of indicators were highlighted at the Birmingham workshop as being a priority for inclusion in a 4 Nations scheme are missing. Other observations on these national or UK level datasets include that:

- The most consistent data was on soil chemical properties but when using the data together there needs to be awareness that there are differences in laboratory methods
- Water retention was identified as a key indicator of soil health but there is very limited data available with only NSIS (Scotland) and BioSOIL (UK) containing any soil water data
- Although horizon depth was identified as an indicator, some datasets only include a single, one off, measure of soil horizons with no subsequent re-sampling. In these instances, only topsoil samples have been taken. However, there are datasets (NSI, England and Wales and NSIS, Scotland) where full soil profile descriptions are available, and where horizon thickness could be remeasured to assess change
- There was limited data on subsoils with typical measurement based on fixed-depth intervals (for example, BIOSoil) rather than soil horizons as with NSIS
- There were fewer standard protocols established for biological indicators
- Data on bulk density was not available for all datasets although it is becoming a more common measurement
- Data on biological parameters and emerging contaminants were included in some of the sampling schemes, but this has been identified as data that could be added if sites were reanalysed
- The lack of some parameters such as enzyme activity in more extensive datasets was likely to be due to the complexities of carrying out the analyses and then need for rapid analysis after sampling

Initial observations highlight the need to properly record and analyse metadata associated with sampling when looking to use datasets to make assessments across the 4 Nations.

No current dataset from any of the 4 Nations contained all of the indicators ranked at the workshop as being most important for soil monitoring. For example, considering the potential soil physical indicators, of the 4 top ranked soil physical indicators only NSIS and possibly BioSOIL (UK) database have some measure of each. Regarding chemistry indicators, 6 of the datasets contained all of the top 4 ranked chemical indicators and within biological databases, no database contained all the indicators viewed as important. **Within UK and National datasets no existing single database has assessed the full breadth of soil physical, biological and chemical health indicators.**

A number of additional datasets were identified that could be considered when looking at changes and identifying the state of specific ecosystems. These include:

- Data from the British Geological GBase chemical sampling which includes data on urban soils, something missing from most other datasets
- Data from specific ecosystems such as machair and oroarctic (montane) surveys in Scotland
- Soil profile data collected for characterising soil types during soil mapping

- Data from on farm sampling from both commercial and government sampling schemes which if combined with the appropriate metadata on lab and field methods and locations could provide high resolution data to assess changes in cultivated systems

Key points

- **Within national or UK level datasets, a number of indicators were highlighted at the Birmingham workshop as being a priority for inclusion in a 4 Nations scheme are missing**
- **Initial observations highlight the need to properly record and analyse the metadata associated with sampling**
- **No current dataset from any of the 4 Nations contained all of the indicators ranked at the Birmingham workshop as being most important for soil monitoring**
- **Within UK and National datasets no existing database assesses the full breadth of soil physical, biological and chemical health indicators**
- **Full opportunity to assess 4 Nation alignment is limited due to the scope of indicators used in existing UK and National datasets**

4. Integrating data sources

Official governmental monitoring schemes are not the only potential source of soil data that could be useful for monitoring soil condition. There are soil samples taken by farmers, including those funded by wider schemes such as those run by companies such as First Milk, Diageo and Sainsburys etc., as well as sampling undertaken by carbon credits organisations, enhanced payment by Scottish Government (data not currently available) and citizen scientists. These diverse data sources could provide valuable information to track soil condition at different scales, and data integration methods have been developed in various fields that could be used within the soil context (e.g., in species monitoring, see Isaac *et al*., 2020). However, there are several important questions that need to be addressed before considering integrating different sources of soil data together.

First, **different soil measurement methods vary in both the accuracy and the precision of the soil property that is being measured**. For example, sampling in one location in a field, at a ‘point’, versus sampling in a ‘W’ pattern across a field and bulking the sample affects the uncertainty associated with estimates of soil properties and potentially how representative this information is. Information on the precise **soil sampling methodology needs to be made available along with the raw data in order to account for methodological differences** (see the metadata discussion in Sections 3, 6 and 7). Additionally, more affordable soil measurement methods, such as the Visual Evaluation of Soil Structure (VESS), may not provide the detail and accuracy required to monitor soil structure at a national scale. However, other methods may be more useful for national monitoring and as such every method would need to be assessed individually for their potential. As an exemplar of how non-traditional methods assessment could be done, within the water quality sector the CaSTCo project has audited the applicability of multiple water quality indicator methods. This assigns indicator measurement methods to different tiers and purposes, showing which are better for engagement purposes only and which could be useful for wider surveillance (**Figure 3**). Examples of such approaches in Scotland include the National Soil Inventory of Scotland (NSIS), indicative of a Tier 1 approach, and the East of Scotland Farm survey which might be viewed as a Tier 3 approach. Further examples may be found in the “Overview of National Soil Monitoring Schemes Across the Four Nations of the UK”. Similar efforts to identify which measurement methods are useful for measuring soil health would need to take before considering data integration. One of the demonstration catchments (River Arun) in CastCo compares different monitoring methods from ‘traditional’ monitoring to observations or measurements undertaken by a farmer. This tiered approach could be adapted for soil monitoring with tier 3 conducted at a national scale by fully competent soil scientists and tier 2 more focused on specific land covers/uses.

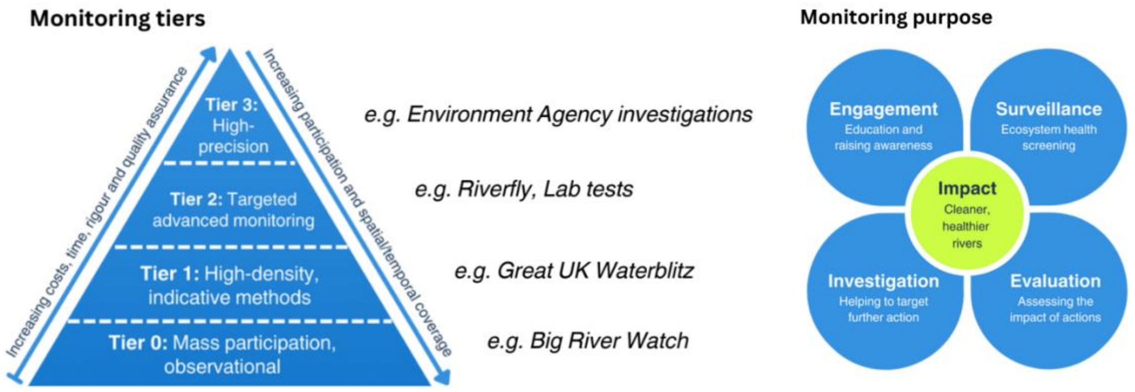

Figure 3. Different monitoring tiers where each indicator is assigned highlighting potential monitoring purpose, taken from CastCo Impact Report

Second, **soil sampling not undertaken as part of a structured survey has a greater risk of bias**. As a simple theoretical example, if farmers only measure soil nutrients in fields that are declining in productivity, then any farmer-derived soil data will be biased towards underestimating soil nutrient content. This is also true for tracking change, as there are likely to be changes in what areas are sampled over time as well as there being no guarantee that any biased subsample will show similar trends over time to the overall population (for an example of this in vaccine uptake survey data, see *Bradley et al*., 2021). Within ecology, there have been frameworks developed for assessing the risk of bias across different data sources (e.g., the ROBITT framework, Boyd *et al*., 2022). A similar framework could be applied when considering integrating soils data from different sources.

Third, **different data sources can come with different usability and ownership constraints**. Soil quality is in many cases a sensitive, and potentially commercially sensitive, issue. Data owners may not wish to make their data openly available, or available directly to government. Some data collectors may wish to keep ownership and control over their data, particularly if this it includes information such as the precise location or if it is collected by groups that feel underrepresented. In some cases, consideration of aspects CARE principles for Indigenous Data Governance may be appropriate. These principles (Collective benefit; Authority to control; Responsibility; and Ethics) set out the rights of indigenous communities to control and access their data in the context of increasing emphasis upon the importance of FAIR (Findable, Accessible, Interoperable and Reusable) data (Research Data Alliance, 2019; Carroll *et al*., 2021). While recognising that not all of these principles will apply in all cases, ensuring responsible and ethical use of non-governmental soils data will require direct and open dialogue with the communities and organisations that collect and own this data.

These three points highlighted above would need to be addressed before integrating data from non-monitoring schemes to analyse status and trends in soil health. It is worth noting that some of these concerns are also applicable to integrating data from different monitoring schemes – e.g., the differences in sampling methodology would need to be considered even when each scheme uses a well-established method. It is also worth noting that the points enumerated above would need to be considered with respect to individual indicators, data collection schemes, and the question of interest (e.g., a scheme may be useful for tracking soil change in forest soils but not more generally). This scoping activity would also have to be revisited over time as sampling activities change, including those within national monitoring. Additionally, there is value in considering the possibility of applying adaptive monitoring principles within national monitoring design. Adaptive sampling is where the data already collected informs a sampling design that changes over the course of the study in response to data collected (Henrys *et al*., 2024). As data can be used from a variety of sources in determining the overall sampling design, this results in a more flexible approach that takes greater advantage of changes in alternative data sources.

Key points

- **Different soil measurement methods vary in both the accuracy and the precision of the soil property that is being measured**
- **Soil sampling not undertaken as part of a structured survey has a greater risk of bias**
- **Different data sources can come with different usability and licensing constraints**

5. Soil archive

A curated archive allows samples to be analysed at a later date for parameters that were not analysed at the time of sampling, due to factors such as budget issues or focus of the original project. One example of the value of having an archive would be **later analysis** for trace elements, heavy metals or plastics, when further funding becomes available or **when a specific environmental, public or animal health issue arises in the future**. Archived soil material is also crucial to future-proof sample analyses where techniques or measurement instruments may have changed allowing back-calculation of all or a subset of original samples to be reanalysed and changes accounted for.

Storage of samples in such an archive will influence the future opportunity to re-analyse with dried, ground samples relatively easy to store for long periods. Samples frozen to -20°C or -80° however are beneficial for soil biological metrics but such equipment is expensive and space within them is finite.

The added value of an archive is outlined below:

1. **Re-analysis with better methods**
    - Testing more sensitive approaches or application of new techniques (e.g., new biomarkers, isotopes, DNA methods)
    - Retrospective analysis
2. **Creating a baseline for change**
    - Reference point to allow comparison over longer temporal changes in land-use, climate or management practices
    - Tracking long-term trends in SOC, nutrients, contaminants, acidification
3. **Quality control and verification**
    - Re-measurement to check old results or resolve data disputes (see NSIS example following this section)
    - Delivery against long-term monitoring networks, carbon projects, and regulatory reporting
4. **Supporting carbon and nutrient accounting**
    - Potential to deliver robust evidence of past soil C and N stocks
    - Support/disprove claims about long-term sequestration, degradation or recovery
5. **Studying contaminants and emerging pollutants**
    - Testing archived soil for “new”, or newly discovered, contaminants (e.g., microplastics, PFAS, new pesticides) found since samples originally collected (note that such retrospective analyses could depend on sample storage medium e.g., samples stored in plastic containers have limited scope for measuring changes in soil microplastics)
    - Helps reconstruct contamination histories
6. **Linking soil to biodiversity**
    - Later applications for **DNA / eDNA** work (microbes, flora and fauna)
    - Comparison of specific aspects of past soil biodiversity to the present
7. **Method comparison and harmonisation**
    - Re-analysis of samples and application of different methods or in different laboratories
    - Calibration of new methods to harmonise datasets across countries or programmes
8. **Education and reference collections**
    - Diversity of soils providing valuable resources for teaching, training, and calibration of field descriptions
    - Serve as a “reference library” of key soil series, horizons, or land uses
9. **Legal and forensic uses**
    - Act as evidence in disputes (pollution cases, land contamination liability, environmental impact assessments)
    - Document soil condition at a known time
10. **Heritage and scientific legacy**
    - Preservation of unique samples from places that may later be urbanised, mined, drained or otherwise lost
    - Scientific “time capsule” of landscapes

Example of existing archives and re-analysis

An existing archive, the National Soils Archive (NSA), is a curated repository for the national collection of Scottish soil samples and is held by the James Hutton Institute. The Archive comprises around 60,000 air-dried samples that have been collected from around 15,000 sites throughout Scotland since the mid-1930s as well as frozen samples from the National Soil Inventory resampling in 2007-9.

The soil samples held in the Archive were collected to characterize the soil map units during the systematic Soil Survey of Scotland (denoted as ‘Selected’ samples in the Scottish Soil Database) as well as the samples from objective sampling schemes, the National Soil Inventory of Scotland (initially sampled between 1978 and 1988) and the repeat sampling (2007-9). These samples were taken from individual soil horizons (layers) from soil profile pits. The Archive also holds samples from long-term and nationally significant experiments and has an associated DNA archive of frozen soil samples, primarily from the National Soil Inventory of Scotland (2007-9).

Before the samples were archived, they were initially air-dried at around 30°C then ground and passed through a sieve of 2mm aperture. Any material >2mm (considered as stones) were discarded. In contrast, the samples retained for DNA analyses were not dried or sieved, instead, the fresh soil was sampled into Eppendorf tubes and frozen at -70°C.

The samples in the Archive are currently stored in unbreakable, 250ml plastic powder jars. Plastic was chosen as the preferred storage medium partly as many of the older sample containers were also plastic and many of these had become brittle over time and, in the early 2010s, the samples were re-potted and it was decided to continue storing them in plastic rather than switching to the more inert but fragile glass containers. Thus, the risk of losing a sample through breakage was deemed greater than using a plastic container. Some of the long-term topsoil (0-15cm) samples from soil fertility experiments (conducted from the 1950s to 1980s) are stored in cardboard tubes with minimal contact with plastics. Moreover, samples from the Trends in Pollution of Scottish Soils sampling scheme to quantify POPs and heavy metals in Scottish soils are stored in glass jars.

As the archivist cannot be sure how a subsample withdrawn from the Archive has been treated any portion of an archived sample taken from the powder jar for analyses and not fully used, is never returned to the same jar. Similarly, samples that are ground to a finer powder, for example, for infra-red analyses are not returned but are stored separately in glass vials. By further grinding the sample, the proportion of finer soil particles is increased and would alter the soil texture of the sample if returned to the sample jar.

A significant value of an archive is that **samples can be used to determine new and novel soil properties using techniques that were not available at the time of sampling**. Another clear benefit to be derived from properly storing samples in an archive is where methodologies or even analytical instruments have changed over time. An example of this was seen when investigating changes in soil carbon concentrations when resampling the National Soil Inventory of Scotland (NSIS) in 2007-9 and comparing to original samples collected 1978-88. When the new sample carbon concentrations were compared to the data from the original Inventory, there appeared to be decline in carbon concentration. However, comparisons between the original and new values for loss on ignition (another measure of organic matter) showed no such difference. Subsequent re-analyses of the original sample alongside the new samples using the same methods and analytical instrument, showed that there was no significant difference overall and that the likely source of the apparent decline was simply due to a change in the analytical instrument used to analyse the soil (**Figure 4**). Therefore, **for a monitoring scheme, it is important to not only compare data overtime but to have the capacity to re-run the analyses if instruments or procedures change** and to have **archived sufficient material to re-analyse the sample a number of times at each successive sampling campaign**.

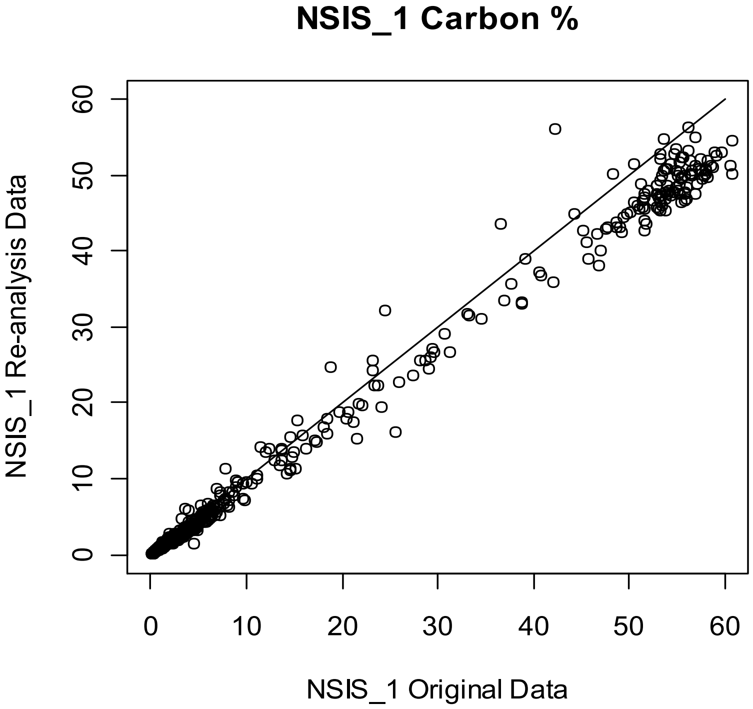

Figure 4. Plot showing original NSIS 1978-88 (NSIS_1) values for carbon concentrations against the reanalysed archive sample showing an inflation of around 11.5% in C concentrations in the original data.

Key points

- **An archive would allow for a comparative analysis when a specific environmental, public or animal health issue arises in the future**
- **Samples can be used to determine new and novel soil properties using techniques that were not available at the time of sampling**
- **For a monitoring scheme, it is important to not only compare data overtime but to have the capacity to re-run the analyses if instruments or procedures change**
- **Critical to archive sufficient material to re-analyse the sample a number of times at each successive sampling campaign**

6. Considerations for data sharing and governance

There are many positives to harmonising, sharing and consolidating soil data across the 4 Nations such as:

- Advancing scientific understanding of soil systems and soil health, which contributes to more informed, evidence-based decision making.
- Potential to improve efficiency with agreed metrics and common guidance provided
- Opportunity for improved transparency and robustness in the collection, use and interpretation of soil data across sectors
- Fostering more long-term commitments to collaboration and innovation into soil health and associated environmental co-benefits

Consolidated soil datasets would provide a useful resource for climate and carbon modelling, inventory reporting, carbon markets and corporate Environmental, Social, and Governance (ESG) reporting, biodiversity assessments, natural capital and wider environmental metrics utilised in policy and land management decisions. However, data are often collected using different methods for specific purposes, held across different institutions, councils and/or countries, and not always in an easy to read/interpret format. Some common issues in consolidating datasets include:

- Inconsistencies/incompatibility in definitions, methods, units, formats, software used
- Ensuring legal and regulatory risks are considered and accounted for (such as GDPR)
- Security: moving and holding data requires secured space
- Data ownership and governance
- Resources required for data management and maintenance over time

As highlighted by Wilkinson *et al*., (2016), the FAIR principles provide a simple template to guide the management and harmonisation of scientific datasets. The principles include;

F – to be findable:

- F1. (meta)data are assigned a globally unique and persistent identifier
- F2. data are described with rich metadata (defined by R1 below)
- F3. metadata clearly and explicitly include the identifier of the data it describes
- F4. (meta)data are registered or indexed in a searchable resource

A – to be accessible:

- A1. (meta)data are retrievable by their identifier using a standardized communications protocol
- A1.1 the protocol is open, free, and universally implementable
- A1.2 the protocol allows for an authentication and authorization procedure, where necessary
- A2. metadata are accessible, even when the data are no longer available

I-to be interoperable:

- I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation
- I2. (meta)data use vocabularies that follow FAIR principles
- I3. (meta)data include qualified references to other (meta)data

R-to be reusable:

- R1. meta(data) are richly described with a plurality of accurate and relevant attributes
- R1.1. (meta)data are released with a clear and accessible data usage license
- R1.2. (meta)data are associated with detailed provenance

- R1.3. (meta)data meet domain-relevant community standards

These act as guides to data publishers and stewards to assist them in evaluating whether their implementation choices are rendering their digital research artefacts Findable, Accessible, Interoperable, and Reusable (Wilkinson *et al*., (2016). Therefore, providing an initial prerequisite for more advanced data management and stewardship.

There is a **considerable quantity of 4 Nation soil monitoring data that has been collected and analysed over the years, yet not all of this is openly accessible**. While there are many good reasons to not make all soils data publicly available (e.g., limits to data sharing agreements created historically), there are still many opportunities to move more of the existing and newly collected soils data into greater adherence of FAIR principles.

A core part of establishing FAIR data is the development of metadata with shared language that contains sufficient attribute information to enable reusability. A formal metadata language, with shared vocabularies and ideally machine-readable fields, also enables findability and interoperability and should be adopted for soils. **The wide variety of soil sampling methodologies means that ensuring data is shared with sufficient and accurate metadata is essential for aligning and harmonising soil monitoring across the 4 Nations**.

While the FAIR principles focus on digital data, soil sample storage and archiving is also essential to the monitoring of existing and emerging threats to soil health.

In terms of a harmonised 4 Nations soil monitoring approach, considerations for inclusion include:

- Data accessibility and usability - what needs to be considered across the 4 Nations?
- Identifying the practice/process (e.g., through policies/procedures) of managing the integrity, accessibility, usability and security of data (e.g., setting out an agreed terms of an ‘aligned monitoring scheme’)
- Exploring options for data management in the execution of the policies/procedures to compile and use the data for decision-making
- Options to ensure data integrity and traceability - what core metadata would be ideal for aligned monitoring?
- Date and location, site description/soil classification, sampling method, sample depth/horizon as appropriate to the scheme, date and location
- Privacy issues when describing site location and description; accessibility – is it open to all or just policy/research? user friendly? digital format, understanding context and limitations (appropriate interpretation and/or extrapolation)

There are existing schemes in the UK which could support the development of a 4 Nations approach. In the Northern Ireland Soil Nutrient Health Scheme, the farmer owns their data, and AFBI holds it for research purposes. Farm level data is not available publicly however is presented/mapped at catchment/regional scale whereby no individual farmer can be identified. A slightly different approach is being adopted within the Northern Ireland Countryside Survey where data will be publicly available on the DAERA and UK-CEH websites following an embargo period to allow all reports to be published. Individual landowners cannot be identified.

The absolute value of soil data is being increasingly recognised by multiple stakeholders. With the landscape changing in both demand, and use of both historic and newly collected data, it is critical to understand what data is, or has been, published under the FARI principles. **It is recommended that a review be carried out to understand data accessibility, based on FAIR principles, of datasets previously highlighted at the February 2024 workshop in London.**

Understanding and monitoring the status and trends in soil health across the 4 Nations requires access to soil data. There is an opportunity to bring data from historic, current, and future soil monitoring schemes into greater alignment with FAIR principles, through activities such as developing a shared metadata vocabulary or even developing a soils data commons approach (Grossman, 2023). Soils monitoring data, both digital data and physical soil samples, are a valuable resource within our increasingly data driven world, and increasing their accessibility maximises the potential of existing data to contribute to a variety of sectors. Therefore, **a key pillar of achieving harmonisation across soil monitoring schemes needs to be consideration of soils data management and governance**.

Key points

- **Consolidated soil datasets would provide a useful resource for climate and carbon modelling, inventory reporting, carbon markets and corporate Environmental, Social, and Governance (ESG) reporting, biodiversity assessments, natural capital and wider environmental metrics utilised in policy and land management decisions**
- **A considerable quantity of soil monitoring data has been collected and analysed over the years, yet not all of this is openly accessible**
- **Variety of soil sampling methodologies means that ensuring data is shared with sufficient and accurate metadata is essential for aligning and harmonising soil monitoring across the 4 Nations**
- **Soil sample storage and archiving is also essential to the monitoring of existing and emerging threats to soil health**
- **Recommended that a review be carried out to understand data accessibility, based on FAIR principles, of datasets previously highlighted at the February 2024 London workshop**
- **A key pillar of achieving harmonisation across soil monitoring schemes needs to be consideration of soils data management and governance**

7. Future opportunities and needs

The workshop in Birmingham 2025 provided an opportunity to understand what the perceived challenges were within the key organisations supporting each government/devolved administration in the adoption of a 4 Nations soil monitoring scheme.

Generally, **monitoring outputs should be designed to be useful for land managers, policy makers, regulators and corporate**. In the near term, there is a **need to prioritise robust trend detection; in parallel, support research and expert processes to define realistic, land-use- and soil-type-specific thresholds**.

Further work is required to understand the resolution requirement for schemes reporting to different users of data (e.g., food supply chain and government reporting), acknowledged in the report under data sharing and governance. There is a need for clearer, more coherent messaging, from the soils community and for improving soils literacy so soils are seen as dynamic, living systems linked to human and ecosystem health. **Coherent messaging is key to avoid confusion which can sometimes result from information that can appear to be contradictory** but only due to critical information not being highlighted that relate to specific instances (such as soil texture, land-use etc.).

Topsoil is the horizon of soil most commonly measured however, subsoils are critical in the delivery of multiple functions and services including water storage, deeper SOC and long-term resilience and are underrepresented in many schemes and datasets collected to date. With many indicators focussing on topsoil only, **subsoil indicators are viewed as a gap that future monitoring should address.**

Although not a core component of the project, collation of all the information gathered as part of this project allows a summary of potential opportunities in establishing a 4 Nations Soil monitoring approach. To do this however, certain criteria should be acknowledged requiring further work prior to adoption:

1. Clear purpose

- Define and communicate a shared, long-term purpose for monitoring: to safeguard soils as a vital national asset that underpins climate, biodiversity, water, food security and public health
- Embed soil monitoring in legislation and core governmental architecture so it is resilient to policy cycles and shifting political priorities
- Ensure the framework is designed to serve multiple policy areas simultaneously (not just one flagship policy), to build resilience and justify sustained funding

2. 4 Nations coordination with national flexibility

- Establish a common UK-wide framework with a core set of indicators, such as those previously outlined in **section 2**. Further work is required to propose methods, depths and metadata requirements to enable comparison, aggregation and joint reporting across the 4 Nations
- Out-with the core indicators, each nation may add complementary indicators, sampling intensities or focus areas that reflect national priorities, provided they do not compromise UK-wide comparability of the data and metrics
- Use the framework to foster regular exchange, learning and innovation between the 4Nations (e.g., shared protocols, training, joint analysis workshops). This is a key recommendation with an annual workshop over 2 days, one day focusing on policy needs with the second day allowing the soil science community to consider requirements with agreed messaging

3. Holistic, functional oriented indicator selection

- Select indicators to reflect key soil functions (e.g., biomass production, water regulation, carbon storage, habitat provision, nutrient cycling) rather than individual policies

- Use a structured typology of indicators (physical, chemical, biological; contextual vs change-response) to ensure coverage of major functions and to aid communication
- Avoid over-reliance on a single "headline" metric (e.g., carbon); instead, specify a minimum core set that together characterises soil condition and function

4. Balance status, trends and thresholds

- Design the framework to track change over time (trends), with potential to assess whether soils are above or below agreed thresholds for degradation or good status. Further work is required to assess the value of such an approach with significant complexity around how thresholds or targets are set
- In the near term, prioritise robust trend detection; in parallel, support research to define realistic, land-use- and soil-type-specific thresholds
- Be explicit which indicators are currently used for trend monitoring only and where thresholds are sufficiently mature to support regulatory or target-based assessments

5. Harmonised methods with managed evolution

- Agree common minimum standards for sampling, sample preparation, and potentially analytical methods which may be different within, and between, the 4 Nations, and quality control across the core indicators
- Where methods must change (e.g., for new technologies), plan overlaps and comparison studies so that conversion relationships can be established. This highlights one significant value of a 4 Nations archive with the example from Scotland highlighting how this has helped in validating soil carbon assessment
- Create and maintain shared guidance on method choices and acceptable alternatives, acknowledging that perfection should not delay implementation

6. Tiered, cost-effective measurement strategy

- Adopt a tiered analytical approach in which all sites receive a core suite of relatively low-cost, robust measurements, while a subset is subject to more intensive and experimental analyses (e.g., detailed biological metrics, novel contaminants)
- More intensive analyses and sampling to fit in with devolved policy issues and to potentially maintain links with past sampling schemes. Further work should investigate what this might look like in each of the 4 Nations
- Use sampling design and stratification to balance spatial coverage, statistical power and depth of information
- Periodically review the tiered design (if adopted) considering new methods, costs and policy demands

7. Explicit treatment of subsoils and vertical structure

- Include subsoil horizons in the monitoring design where they are critical to functions such as water storage, rooting, compaction, carbon storage and resilience
- Standardise depth intervals (e.g., topsoil and at least one subsoil layer) while documenting horizon boundaries and soil profile changes where feasible. Much of this has already been developed within international standards, however this should be incorporated within a potential 4 Nations scheme
- Ensure that subsoil data are clearly distinguished and analysed alongside topsoil data rather than being ignored. The sampling frequency for subsoils should be studied further to understand potential rates of change and therefore cost-effective temporal sampling

8. Robust data stewardship, access and licensing

- Develop common principles and practical solutions for data licensing that maximise access and re-use while respecting privacy and commercial sensitivities
- Ensure that key datasets are findable, accessible, interoperable and reusable (FAIR), with associated rich metadata on methods, land management, soils and site context
- Provide clear pathways for incorporating non-traditional data sources (e.g., citizen science, farm records, corporate monitoring), including standards for assessing quality and fitness for purpose

9. Communication, soils literacy and stakeholder usability

- Design outputs, dashboards and summary statistics that are usable for different audiences: policy makers, regulators, land managers, businesses and the public
- Invest in improving soils literacy so stakeholders understand soils as living, dynamic systems linked to wider ecosystem and human health. It is noted that there are currently EU Horizon projects which are seeking to address these issues and may provide readily accessible resources
- Develop a consistent UK-wide narrative and set of messages about soil condition and trends

10. Flexibility for future issues and innovations

- Future-proof the framework by enabling periodic review and updating of indicator sets, especially for emerging threats (e.g., "forever chemicals", microplastics) and new biological methods (e.g., eDNA, metagenomics)
- Use archives and harmonised metadata to enable retrospective application of new indicators without losing time-series continuity
- Maintain an innovation pathway (e.g., pilot studies, use of Living Labs and other networks, method evaluation) that can bring promising new indicators into the core set once they are mature

11. Alignment with wider environmental monitoring

- Where possible, align soil monitoring with other environmental observation systems (water quality, air quality, biodiversity and ecosystem health indices) to enable integrated assessments
- Use shared sites or co-located sampling where feasible to strengthen cross-media understanding and cost-efficiency
- Ensure that soil data can feed into national and international reporting obligations (e.g., greenhouse gas inventories, biodiversity and land degradation commitments). Further work, however, is required to do this with the EU Soil Monitoring Law not considering sampling and data requirements for Land Use, Land-Use Change, and Forestry (LULUCF)

Key points

- **Monitoring outputs should be designed to be useful for land managers, policymakers, regulators and corporate reporting**
- **Prioritise robust trend detection; in parallel, support research and expert processes to define realistic, land-use- and soil-type-specific thresholds.**
- **Further work required to understand the resolution requirement for schemes reporting to different users of data (e.g., supply chain and government reporting)**
- **Coherent messaging is key to avoid confusion which can sometimes result from information that can appear to be contradictory**

8. Challenges

The main challenges identified by respondents in progressing 4 Nation monitoring of soils:

- **Policy and Priorities:** There are significant differences in policy drivers, governmental priorities, and established programmes across the 4 Nations. This leads to difficulties in agreeing on what should be measured and which indicators to prioritise
- **Funding:** Inconsistent and patchy funding cycles, as well as differing funding priorities, are seen as major obstacles
- **Methodological Alignment:** Highlighted the challenge of harmonising methodologies, including sampling designs, protocols, and definitions (e.g., metrics, indicators, parameters). There's concern about comparability if each nation measures things differently, but the scientific community is aware of these with knowledge around how these can be overcome and they shouldn't be viewed as a barrier
- **Data and Legacy Issues:** Different legacy datasets and the need to protect historic time series data make it more difficult but not impossible to align new monitoring efforts
- **Agreement and Buy-in:** Achieving agreement on the need for a unified approach, as well as securing buy-in and mandate, are seen as hurdles
- **Technical and Contextual Differences:** Differences in soil context, land use, and soil functionality across the 4 Nations make the development of a unified scheme challenging but nonetheless achievable
- **Maintaining Momentum:** Sustaining long-term commitment and momentum for the scheme is a concern
- **Training and Quality Assurance:** for surveyors are critical with the perception that there are insufficient skilled workers to address the potential needs of soil monitoring

Key point

- **The key challenges are in aligning policy and funding, harmonising data, and achieving agreement and sustained commitment across the 4 Nations**

9. Conclusions

This report has highlighted that there is a significant opportunity to align soil monitoring across the 4 Nations of the UK with broad agreement on the metrics that should be included. Timing is critical, with Scotland currently developing their soil monitoring framework and Northern Ireland working to understand what future monitoring should look like following on from their Soil Nutrient Health Scheme. The EU formally adopting the Soil Monitoring and Resilience (Soil Monitoring Law) in October 2025 and potentially coming into effect in 2032/33.

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Appendix 1. Nine national and UK wide datasets and methods used to assess alignment

County	Survey	Description	Land cover	Design	Resolution/Sample Numbers	Temporal
England and Wales	**NSI**	Soil profile descriptions and classification to soil series level with samples takes from 0-15 cm with a 2.5 cm Auger to a maximum depth of 15 cm	All	Grid (5 km)	1978-1983 (5,662 sites)	1994/95 for arable and rotational grassland (853 of original 2,578 sites); 1995/96 for managed permanent grassland (771 of 1,579); 2003 for non-agricultural (555 of 1,505)
England	**NCEA**	Soil profile descriptions (Pit to 60 cm and auger to 120 cm) and samples taken and bulked at 4 points around a central vegetation plot (16 m) Depths (0-15 cm, 15-30 cm and 30- 40 cm)	All	Sampling of Monads based on soil classes, cland cover and broad habitats	March 2023 (69 monads/215 plots)2024-2025 (400 monad/1600 plots average).	Cyclical survey every 5 years (monitoring of changes on the same sampled plots) Main September -March 2023 March-June
Scotland	**NSIS**	Soil profile descritions availble on a 5 km grid samples taken by soil horizon to 1 m depth.	All	Grid based samplin 1978-88 5 km grid with samples dtaken every 10 km , Resampled 2007-09 on a 20 km grid.	NSIS2 - 184 sites + Rare Soils 1978-88 721 sites	2 Samples 1978-88 (Spring and Autumn),and 2007-09 (Spring)
Northern Ireland	**NI SNHS**	Every field sampling of topsoils 0-7.5 cm in grassland and 0-15 cm in arable with a focus on nutrients	Cutlivated land (Impoved Grassland and Arable)	Aggregated sample	Every field	One off sampling
Northern Ireland	**NICS**	0-15 cm soil sample. No soil description or classification	All	Stratified random sample of 1 km squares according to land class. In-line with GB Countryside Survey methods.	2023 & 2024 (288 squares: vegetation, linear features + soils)	2023-24 May to September
Wales	**ERAMMP**	0-15 cm soil sample. No soil description or classification	All	Stratified random sample of 1 km squares according to ITE land class, contains subset of CS squares	2013-2016 (300 squares, 1500 sites)	Initially 2021-2024 and now a rolling programme, May-September sampling
UK	**BioSOIL**	Pedological characterisation at start of survey. Soil profiles described and sampled for 80 cm based on depth sampling Organic layer then 0-5 cm, 5-10 cm, 10-20 cm, 20-40 cm and 40-80 cm	Forestry	16 x 16 km national grid. Sites were selected on the basis of the presence of woodland of >0.5 ha.	More than 220	Sampling every 10-20 years
UK	**Countryside Survey**	0-15 cm soil sample. No profile description or classification	All	Stratified random sampling of 1 km squares acording to land class	1978 (256; 1289 sites)1998 (256; 1289 sites); 2007 (595; 2666 sites)2020-2024 (500;2500).	1978, 1998, 2007, 2020-24 Rolling programme over 5 years May - September
Europe	**LUCAS**	Early sampling 0-20 cm with recent changes to 0-10, 10 - 20, and 20-30 cm added	All	Stratified random sample according to land cover. Slightt bias for agricultural land	2009 (19000 sites)2012 (Only RO&BG; 2000 sites); 2015, 2018 (22,000 sites), 2022 (41,000 sites)	2009, 2015-18, 2022 Discussions re. 2027-28. April - october

Appendix 2. Soil physical indicators and methods within nine national or UK wide datasets

County	Survey	Bulk Density	Soil Depth (Rooting)	Peat depth	Water Retention	Topsoil aggregate stability
England and Wales	**NSI**	No	Just available for first sampling ~1983 mid year	Depth 1st samplind	No	No
England	**NCEA**	Yes	Soil profile descriptions	Soil Profile Descriptions	No	No
Scotland	**NSIS**	All profile horizons in 2007-09 20km sampling by sample rings	Yes - Profile descriptions availble for all profiles 1978-88 and 2007-09	Yes to 1m or rock.	Some data	Mineral topsoils only and only for NSIS 2007-09 by Eijkelkamp wet sieve apparatus.
Northern Ireland	**NI SNHS**	No	No	No	No	No
Northern Ireland	**NICS**	Bulk density calculated based on the dry weight of soil at 105°C minus the stone weight/volume for the 15 cm core. Bulk density is corrected for the sub-sample of fresh soil removed for pH measurement of fresh soil per CSGB methodology.	No	2023 & 2024 Peat rod for depth measured in 3 locations. 'O' Horizon depth recorded	No	No
Wales	**ERAMMP**	Yes	No	O' horizon depth measured by ruler and from 2019 onwards Peat rod for depth measured in 3 locations	No	No
UK	**BioSOIL**	Mandatory to 40 cm optional for non stony soils to 80 cm Core sample Oven dried at, temperature 105°C) Coarse Fragment calculated	Pedological classification at the beginning of survey and litter layer measured as part of sampling. Stone content estimated from soil profile descriptions	separate sampling of the organic layers and mineral soil according to the fixed depth layers. Peat (Histosol (WRB, 40 cm sampled differetnly)	The volumetric water content at matric heads 0, -1, -5, -33 and -1500 kPa plus the dry soil bulk density are mandatory to determine on Level II core plots. Extra observations of the SWRC at pressures -10, -100 and -250 kPa are optional but they greatly improve fitting the soil water retention characteristic (SWRC).	No
UK	**Countryside Survey**	From 2019 Bulk density was calculated based on the dry weight of soil at 105°C minus the stone weight/volume for the 15 cm core.	No	O' horizon depth measured by ruler and from 2019 onwards Peat rod for depth measured in 3 locations	No	2007 only for subset of 750 soils:
Europe	**LUCAS**	Yes	No - Topsoil survey only	Check for depth compliance with WRB Histosols (i.e. 10/40 cm)	No	No

Appendix 3. Soil biological indicators and methods within nine national or UK wide datasets

County	Survey	Microbial Community	Enzyme Activity	Respiration (qCO2)	Microanrthopod community Structure	Nematode community Structure
England and Wales	NSI	No	No	No	No	No
England	NCEA	Metabarcoding using Illumina NovaSeq platform (2 x 250 bp) on: 1)Bacteria and archaea 16S rRNA gene (V4) 2)Fungi and mycorrhizal ITS (ITS1)	No	Multisubstrate-induced respiration/fresh samples	No	2)Metacoding of the 18s rRNA gene (V7 and V8) of nematodes (microfauna). Baermann funnel extraction of nematodes, extraction of nematode DNA and final metabarcoding.
Scotland	NSIS	(eDNA- 2007-09) (PLFA Both)	No	2007-09: Basal Respiration:Microresp	No	Some sites sampled 1978-88 had Nematode populations identified. DNA analysis in 2007-09
Northern Ireland	NI SNHS	No	No	No	No	No
Northern Ireland	NICS	No	No	No	No	No
Wales	ERAMMP	GMEP metabarcoding in subset of sites (2013-14): bacterial 16S rRNA, fungal ITS, eukaryotic 18S rRNA	No	No	No	No
UK	BioSOIL	Metabarcoding on ITS, 16S and COI, fungi and mycorrhizal ITS (ITS1)	No	No	No	Metacoding of the 18s rRNA gene (V7 and V8) of nematodes (microfauna). Baermann funnel extraction of nematodes, extraction of nematode DNA and final metabarcoding. Metabarcoding using Illumina NovaSeq platform (2 x 250 bp)
UK	Countryside Survey	PLFA 1998 only; Metabarcoding: CS 2007: Bacterial 16SrRNA (~1100 cores), eukaryotic 18S rRNA (~1100 cores), fungal ITS (~1100 cores), Plant ITS (~700cores), Roche 454 metagenomes (8 cores), AM fungi (1100 cores)	No	2007 only: Subset of 750 intact fresh soil cores incubated at field capacity at 10^{o}C (as for potential N mineralisation) with cores sealed to record respiration rates after standard time.	No	No
Europe	LUCAS	Metabarcoding on ITS and 16S rRNA	No	Yes - on 1000 sites from 2018	No	No but DNA analysis

Appendix 4. Soil chemical indicators and methods within nine national or UK wide datasets

County	Survey	Soil Organic Matter	Topsoil SOC %	Soil pH	C/N ratio	C:Clay Ratio
England and Wales	**NSI**	First sampling, all soils by dichromate oxidation; second sampling, all by dichromate oxidation except those with > c. 150 g kg-1 OC (< 10% of samples) by loss on ignition		YES water 1:2.5	No	Particle-size distribution: pipette method following destruction of organic matter with hydrogen peroxide
England	**NCEA**	LOI using TGA: 375 °C kept constant for 15 h 45' (gives LOI); 650 °C kept constant for 2 h (decomposition of clay minerals and other losses); 1000 °C kept constant for 2 h (CaCO3 content of the sample)	combustion at 1200°C with pure oxygen and IR detector for CO2	pH in1:2.5 water solution	combustion at 1200°C with pure oxygen and TDR detector to analyze nitrogen content	Laser Diffraction (<2mm) method for 0-15 cm, 15-30 cm, 30-40 cm. PSD by sedimentation for 0-15 cm
Scotland	**NSIS**	By loss on Ignition at 450 and 900 degrees C for 2007-9 sampling , 800-900 for 1978-88 samples.	Yes by Flash EA 1112 Series Elemental Analyser connected via a Conflo III to a DeltaPlus XP isotope ratio mass spectrometer (all Thermo Finnigan, Bremen, Germany). Delta 13 C also	Yes in water and calcium chloride (ratio soil to water of 1:3	Yes including delta 15 N	Yes at a range of particle sizes via mastersizer laser. Both USDA and BSTC particle sizes determined. NSIS1 Hydrometer data
Northern Ireland	**NI SNHS**	Determined using loss on ignition: 10 g sub-sample of air dried sample (<2 mm) dried at 102 ± 2°C overnight to remove any residual moisture, weighed and then combusted at 850°C for 30 minutes in a muffle oven. The LOI is calculated as the weight lost after combustion at 850°C.	No (Separate survey of 250 points that had preciously been sampled)	Yes, pH on air-dried soil (v/v 1:2.5) in water	No	No particle size

County	Survey	Soil Organic Matter	Topsoil SOC %	Soil pH	C/N ratio	C:Clay Ratio
Northern Ireland	**NICS**	Determined using loss on ignition (CSGB methodology) 10 g sub-sample of air dried sample (<2 mm) dried at 105°C for 16 hours to remove any residual moisture, weighed and then combusted at 375°C for 16 hours in a muffle oven. The LOI is calculated as the weight lost between 105°C at 375°C. A duplicate sample and two 'in-house' quality control soils are included with each batch of 20 samples to monitor the accuracy and percision of the method.	Total carbon is determined using an elemental combustion analyser.	pH on field moist soils in 1:2.5 soil water suspension and $CaCl_2$ method.	Total nitrogen is determined using an elemental combustion analyser.	No
Wales	**ERAMMP**	LOI (375deg.C for 16 hours) GMEP 2013-2016 but now TGA	% C by combustion using elemental analyser	pH on field moist soils in 1:2.5 soil water suspension. $CaCl_2$ data also available.	%N by combustion using elemental analyser	GMEP 2013-2016 particle size analyser
UK	**BioSOIL**	LOI (375deg.C for 16 hours)	%C by combustion using elemental analyser	pH in1:2.5 water solution and also $CaCl_2$	% N by combustion using elemental analyser	PSD - Hygrometer
UK	**Countryside Survey**	LOI (375deg.C for 16 hours)	%C by combustion using elemental analyser	pH on field moist soils in 1:2.5 soil water suspension. $CaCl_2$ data also available.	%N by combustion using elemental analyser (Total)	Laser analyer for samples from 2019
Europe	**LUCAS**	No	ISO 10694 Determination of organic and total carbon after dry combustion	ISO 10390 for determination of pH in H_2O and $CaCl_2$ extract (pH-H_2O and pH-$CaCl_2$)	ISO 11261 for determination of total soil nitrogen using a modified Kjeldahl method	Sedimentation for 2009/2012 Later surveys: Laser Diffraction ISO13320

GLOSSARY

Term	Definition
Accuracy	How close a measurement is to the true value. This is determined by both analytical technique and field sampling method.
Acidification	The process by which the concentration of hydrogen ions in the soil gradually increases, caused by the removal of slightly alkaline base cations by the crop, leaching and the application of acidifying types of nitrogen (N) fertiliser. This process is accelerated or insufficiently compensated by natural soil components processes and base status of the parent material.
Aggregate Stability	Soil aggregates consist of two or more soil particles bound together by various forces. Soil aggregates comprise of a range of shapes and sizes. Their stability is their ability to resist breakdown. Soils with a greater aggregate stability are more likely to resist compaction and erosion.
Alignment	Agreement on a direction of travel with the same measure being collected to monitor potential change, however, the specific methodologies in each Nation may be different.
Arable land	This is land ploughed or tilled frequently, generally under a system of crop rotation however may also be under monoculture.
Archaeal diversity	A diverse community is indicative of a healthy functioning soil. Soils dominated by a specific subset of bacteria (archaea) are generally considered nutrient replete. Data can reflect impact of land management practices and perturbations on soil.
Auger samples	Soil samples taken using a soil auger.
Base saturation	The degree to which a soil having cation-exchange properties is saturated with exchangeable bases (sum of Ca, Mg, Na, K), expressed as a percentage of the total cation-exchange capacity. The ratio is an indicator of soil fertility and a function of management and soil type and parent material.
Bedrock	The mineral substrate. More or less consolidated rock locally exposed at the surface. The bedrock is also designated as the R horizon in UK soil profile descriptions.
Bias	The degree to which the distributions of values is skewed from a representative distribution of the population of values. If biased samples are compared, it can lead to potential errors in conclusions about the change in values. Soil sampling not undertaken as part of a structured survey has a greater risk of bias. Purposive soil sampling, in which sampling locations are intentionally chosen on the basis of their characteristics, have a greater risk of bias than a random or systematic (e.g., grid-based) sampling scheme.
Biodiversity	The variety of plant and animal life in the world or in a particular habitat, a high level of which is usually considered to be important and desirable.
Biological indicators	A biological measure of the condition or health of the soil based on its ability to function and provide services. Thresholds that define healthy soils will be determined by the soil type and land use.

Biomarkers	Indicators that represent biological processes in the soil. Microbial biomarkers are being explored as indicators of soil functions such as carbon turnover, nutrient cycling and a soils' response to stress.
Biomass	Organic material of biological origin (plants and animals). The term can be used for agro-industrial effluents and waste, energy crops, materials harvested from nature (e.g., wood) or organic wastes. Adding biomass to soils can be used to improve soil fertility and health and increase carbon storage.
Bulk density	The dry mass of soil per unit volume is expressed as kg m^{-3} or g cm^{-3}. Indicates soil porosity and hence, infiltration capacity (affecting runoff), water retention, compaction and conditions for root growth.
C/N ratio	The ratio of soil organic carbon to nitrogen with the ratio determining the release of nutrients to microbes and plants.
Carbon credits	A certificate that represents the increase in soil carbon that represents CO_2 removed from the atmosphere that can be traded for emissions.
Carbon markets	The buying and selling of carbon credits.
CARE principles	Collective benefit; Authority to control; Responsibility; and Ethics for the data governance of indigenous people. https://www.gida-global.org/care
Catchments	An area where precipitation falls inside its boundaries and is either held within the area, or flows (either overland or via drainage pathways) towards a single point or outlet. Also known as a hydrological area, drainage basin or river basin.
Cation Exchange Capacity (CEC)	The capacity of soil to hold and release nutrients for plant use. Specifically, CEC is the amount of negative charge available on clay minerals and soil humus to hold positively charged ions. Effective cation exchange capacity (CEC) is reported for acid soils (pH<5).
Citizen scientists	Usually used to denote a non-professional scientist and may range from the public (including land managers) to highly proficient amateur scientists.
Cultivated land	Land that is worked by ploughing, sowing and cropping including both intensively managed grassland and arable land.
Depth based samples (fixed depth samples)	Samples taken to represent fixed depths (e.g., 0-30cm). These samples may be taken from more than one soil horizon (compared to Horizon based samples).
Depth to water table	Depth to the upper surface of groundwater or the level below which the soil is saturated with water.
Earthworms	A diverse community of all functional earthworm types is indicative of a healthy functioning soil with data potentially reflecting the impact of land management practices and perturbations on soil.
Ecology	The interrelationship of organisms and their environments.
Ecosystem	All of the living things (plants, animals, organisms and people) in a given area that interact with each other and their wider environment.

Ecosystem Services	The benefits arising to humans from the ecological functions of ecosystems. These include provisioning services such as food, water, timber and fibre; regulating services that affect climate, floods, and water quality; cultural services that provide recreational, aesthetic and spiritual benefits and supporting services such as soil formation, photosynthesis and nutrient cycling (Millennium Ecosystem Assessment, 2005). All of the living things (plants, animals, organisms and people) in a given area that interact with each other and their wider environment.
eDNA	Analysis of eDNA provides a non-invasive way to detect organisms from the genetic material they leave behind. In soil, eDNA can originate from bacteria, archaea, fungi, protists, plants, and animals, giving a snapshot of ecosystem diversity and health.
EJP Soils	European Joint Programme Soil, co-funded by the European Commission and by 24 European countries, with a long-term objective to align soil related research at a national and at a European scale.
Environmental and Social Governance (ESG)	The ways in which data is collected, stored, managed and subsequently used for decision making. It includes the recording of data collection protocols and how the data is verified and audited.
Erosion features	Features in landscapes such as rills or gullies or the movement of sheets of surface soil caused by accelerated erosion by wind or water. These indicate poor soil structure or loss of organic matter. Although a natural process, accelerated erosion can be a major process of soil degradation.
EU Soil Monitoring and Resilience Law	Formally adopted by the EU on 29 September 2025 and passed on the 23rd October 2025, the Council of the EU formally adopted at first reading a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law). The new Directive is intended to provide a solid and coherent soil monitoring framework for all soils across the EU, to provide data on soil health in all member states and support the EU Soil Strategy target for healthy soils across the EU by 2050.
EU Soil Strategy	The EU Soil Strategy for 2030 is centred on harnessing the numerous benefits that healthy soils provide, which are vital for human well-being: sustainable food production, biodiversity and climate resilience.
FAIR principles	Findable, Accessible, Interoperable, and Reusable data management.
Fungal communities	A diverse community is indicative of a healthy functioning soil. Soils dominated by fungal communities are generally considered nutrient depleted. Data can reflect impact of land management practices and perturbations on soil. A highly productive agricultural soil is considered to have a 1:1 bacteria to fungal ratio.
Field capacity	The amount of water held in the soil pores against the pull of gravity. Often defined as the water content of the soil 48 hours after rainfall or by measurement of the matric potential (suction).
Food security	When all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences (FAO definition).

Greenhouse Gases (GHG)	Greenhouse gases such as CH_4 methane, CO_2 carbon dioxide and N_2O nitrous oxide.
Gleying	The result of the reduction, mobilisation and, sometimes, oxidation of iron and other elements resulting in the formation of grey colours and ochreous mottles within the soil.
Grid sampling	Sampling at fixed points in a systematic pattern.
Harmonisation	Harmonisation would be the aligning of measures utilising the same methodologies and protocols allowing direct comparison rather than the broader direction of change in each Nation.
Heavy metals	Metals such as Cu, Fe, Mn, Mo, Zn, Cd, and Hg that have a high atomic mass and can be a source of environmental pollution.
Horizon samples	Samples taken from a specific, identifiable layer (horizon) in the soil that has properties (e.g., colour) distinct from the layers above and below. (compared to depth-based samples).
Humus	The dark, amorphous organic component formed through the decomposition of plant and animal residues by soil microorganisms in soils, with a low specific weight and high surface area; usually composed of many organic compounds of high molecular weight. A term often used synonymously with soil organic matter. Humus is a critical component of healthy soils, important for soil fertility and helps to bind soil particles and aggregates together.
Hydrocarbons	Organic substances that are composed of only carbon and hydrogen. Substances such as fossil fuels are a mixture of hydrocarbons.
Improved grassland	Land used for grazing where over one third of the sward comprises, singly or in mixture, ryegrass, cocksfoot or timothy, or land that has been improved by management practices such as liming and top dressing or ploughing, where there is not a significant presence of sensitive plant species indicative of native unimproved grassland.
Infrared analysis	An analytical technique using infra-red light to identify the chemical composition of materials. Fourier-transformed infrared spectroscopy (FTIR), mid-infrared and near-infrared (MIR and NIR) are examples.
Intensively managed	System that maximises yields of arable crops or grass using pesticides and fertilisers.
Isotopes	Atoms with the same number of protons but different numbers of neutrons. Carbon isotopes provide information indicates how carbon is turned over within the soil.
Land Capability for Agriculture (LCA in Scotland ALC in England/Wales and Northern Ireland)	Classification of land on the basis of its potential productivity and cropping flexibility determined by the extent to which its physical characteristics (soil, climate and relief) impose long term restrictions on its agricultural use.
Land Capability for Forestry	Classification of land on the basis of its potential to grow trees and flexibility for growth and management based on a number of factors including soil, climate and topography.
Land cover	The current vegetation or physical material on the soil.
Land management	A collective term describing a range of practices and applications imposed on soil for a range of purposes (e.g., food production, ground preparation, urban development, and conservation). The current vegetation or physical material on the soil surface.

Land use	The dominant activity taking place on an area of land. Within this report land use areas include arable and horticultural fields, grassland, forestry, woodland, wild-scapes and urban.
Leachate	Soluble materials lost from the soil, usually caused by water filtering through it.
Lighthouse	Places for demonstration of solutions, training and communication that are exemplary in their performance.
Living Lab	User-centred, place-based and transdisciplinary research and innovation ecosystems, which involve land managers, scientists and other relevant partners in systemic research and co-design, testing, monitoring and evaluation of solutions, in real-life settings, to improve their effectiveness for soil health and accelerate adoption.
Loss on Ignition	Loss on ignition (LOI) is a widely used method for measuring organic matter content in soils but does not have a standard protocol, for example the temperature at which the which samples are ignited varies with laboratory and can yield different values.
Metabarcoding	Metabarcoding is a high-throughput, DNA-based technique for identifying multiple species simultaneously within a single, complex environmental or bulk sample such as soil.
Metadata	The recording of the collection and analytical protocols for soil samples, the units of measurement. Recorded in such a way that the same sample collection and processing could be repeated in another study.
Metagenomics	Metagenomics is the direct genetic analysis of entire microbial communities from environmental samples such as soil using whole-genome sequencing.
Metric	A quantifiable set of data that can be used to track, compare and assess performance or processes.
Microbial/ Microarthropod community	The diversity of microbes and microarthropods in the soil. These are important for nutrient and carbon cycling and processing in the soil. They also have a role in controlling plant diseases and pathogens.
Microplastics	Plastic particles in the soil that are less than 5mm. These are contaminants in soils that can affect soil functioning and can accumulate in plants, animals and humans where they have been shown to impact health.
Natural capital	The world's stocks of assets from the natural environment, which include geology, soil, air, water and all living things.
Nematode community	A diverse community of all functional nematode groups is indicative of a healthy functioning soil. Due to position in soil food webs, recognised as an integrated indicator of medium to long-term impacts on soil. Data can reflect impact of land management practices and perturbations on soil.
Organic Matter	Plant and animal residue in the soil in various stages of decomposition.

Organic soils	Organic soils are formed under waterlogged conditions or where the natural decomposition rates of organic material are significantly slower than the rates of accumulation. These soils have different definitions within the UK, e.g., in Scotland they have more than 60% organic matter and exceed 50cm in thickness. In England and Wales they have a lower organic carbon threshold and are at least 40cm thick.
Organo-mineral soils	Soils In Scotland, soils with topsoil organic carbon concentrations greater than 35% and less than 50cm thick. The term should not be confused with organic-mineral which is used to denote a highly organic-rich topsoil.
Oroarctic	Climatic conditions found on mountain tops particularly in Scotland where the climate is similar to arctic or sub-arctic.
Packing density	Packing density is proposed as a proxy indicator for soil compaction and derived from measures of soil bulk density and clay content.
Particle Size	The size of soil particles (categorised as sands, silt and clays). This affects soil erodibility (susceptibility to detachment, transport and deposition), depending on the energy of the eroding agent. Particle size also affects specific surface area which determines the capacity of soil to absorb nutrients, contaminants, and hydrology. The proportion of the different article sizes in a soil is measured on the <2mm fraction.
Pathogens	A pathogen is any organism or agent, such as bacteria, viruses, fungi, or protists, that causes disease in a host.
Peat	Peat is a type of soil formed in waterlogged conditions from incompletely decomposed plant material. Peat forms in wetlands or peatlands, also commonly called bogs, moors, mires, swamps and fens.
Peatland	Often called bog, are wetland ecosystems with soils which are saturated and hold large deposits of dead organic material in different stage of humification (peat). In good conditions, peatland habitats are dominated by a mixture of *Sphagnum* mosses, cotton-grass (*Eriophorum* spp.), and dwarf shrubs.
Pedological feature	Features within the soil that have developed over time in response to drivers of soil formation and are used in soil classification and an understanding of how it functions.
Pedology	The study of soil processes that affect soil development and the classification of soils.
PFAS (Forever chemicals)	Per- and poly-fluoroalkyl substances (PFAS) enter the environment via various sources and may accumulate in soil and groundwater which have been linked to health impacts.
pH	Measure of acidity (Hydrogen and Aluminium ions), measured from 1 (acid) through 7 (neutral) to 14 (alkaline) expressed on a logarithmic scale. Most soils have a pH 3 to 9.
Physical indicators	A physical measure of the condition or health of the soil based on its ability to function and provide services. Thresholds that define a healthy soil will be determined by the soil type and land use.
POPs	Persistent Organic Pollutants are organic pollutants that resist breakdown and decomposition in the environment.
Pore size distribution	The volume and size range of pores in the soil.
Porosity	Total volume of pores in a soil.

Remote sensing	The measurement of properties from remote methods for example satellites or drones. This can include spectral images (visual, infrared, radar) and terrain and vegetation surfaces from methods such as LiDAR.
Soil classification	Soil classification (also termed soil taxonomy) is the scientific discipline of grouping soils according to similar or comparable soil forming properties and that exhibits a similar sequence of soil horizons. Many countries in the world have national soil classification systems but those of World Reference Base and the US Soil Taxonomy are used internationally.
Soil compaction	Soil compaction is a form of physical degradation in which the larger soil pores are compressed by increasing the bulk density of the soil and decreasing its porosity. This has implications for soil biological activity and soil productivity for agricultural and forestry are reduced. Increased runoff due to compaction increases the likelihood of flooding and erosion, resulting in environmental consequences away from the immediate area directly affected.
Soil contamination	The presence of a chemical or substance in the soil in a concentration that may be harmful to human health or the environment. Contamination may have a direct toxic effect on the plants, animals or humans living in, on, or from that soil, or have an indirect toxic effect due to accumulation in the whole trophic chain.
Soil degradation	The physical, chemical and biological decline in soil quality.
Soil erosion	Soil erosion due to detachment and transport of soil particles or aggregates by rainfall, runoff or wind. Co-extraction with harvested crops and adhesion to agricultural vehicles and implements can also lead to significant soil losses. Units are usually soil mass lost per unit area per unit time.
Soil function	Soil function refers to the six key roles that soil plays in an ecosystem, including providing a medium for plant growth, supplying and purifying water, recycling nutrients and organic wastes, serving as a habitat for soil organisms, modifying the atmosphere, and acting as an engineering medium.
Soil health	Healthy soil is a continued capacity of soil to function as a vital living system. Soil is the basis of 95% of our food. If soils are healthy, they provide essential ecosystem services such as clean water and habitats for biodiversity. They are major carbon reservoirs, which help slow the onset of climate change while making us more resilient to extreme climatic events. Soils are a key part of the landscapes that we all cherish and are the basis of our economy and prosperity.
Soil indicator	A measure of a soil property that is indicative of the condition or health of the soil based on its ability to function and provide services. Thresholds for indicators will be determined by the soil type.
Soil monitoring	Tracking trends in quantitative indicators or the functional capacity of the soil to determine the success of management practices or the need for additional management changes, or the effects of climate or land use change. Monitoring involves the orderly collection, analysis, and interpretation of data from the same locations over time.

Soil organic carbon	The carbon derived from living and dead plants and animals. It is the principal component of soil organic matter. Often abbreviated to SOC.
Soil organic matter	Soil organic matter means all living, or once-living, materials within, or added to, the soil. This includes roots developing during the growing season, incorporated crop stubble or added manures and slurries. Vital for supporting multiple soil functions. It contains approximately 50% carbon so provides a significant carbon store in organo-mineral and organic soils. Often abbreviated to SOM.
Soil profile	The soil profile is a column of soil, essentially three-dimensional and large enough to be used to identify the layers and characterise the soil condition at a particular place.
Soil quality	The capacity of soil to function, within natural or managed ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water quality, and support health and human habitation.
Soil structure	Soil structure is the ‘architecture’ of soil - how it is constructed and made up. The structure is the aggregation of primary soil particles (sand, silt and clay) into units separated from each other by surfaces of weakness.
Soil texture	Defined by the proportion of soil distributed over specified particle size ranges (categorised as sands, silt and clays) (Brady and Weil, 1990). Texture generally refers to the <2mm fraction of the soil. Soil structure is the ‘architecture’ of soil - how it is constructed and made up. The structure is the aggregation of primary soil particles (sand, silt and clay) into units separated from each other by surfaces of weakness. An individual natural soil aggregate is called a ped, in contrast to a clod caused by disturbance, or a concretion caused by cementation.
Soil type	Soil type is a conceptual and highly generalized unit used in soil science in many soil classification systems. Soil type is defined mainly on the basis of characteristics resulting from soil-forming processes (pedogenesis). Soils have a certain sequence of genetic horizons and certain properties form a specific soil type.
Stones	Coarse fragments found in the soil more than 2mm in diameter.
Thresholds	Thresholds can be considered the point above or below which a soil property can be considered to be at such a level that the soil cannot fully function. Thresholds help to benchmark the state of a given soil compared to a potential.
Topsoil	The surface soil horizon (A) which is modified when cultivated, and designated Ap. Although at the surface, organic surface horizons are not normally designated as ‘topsoil’.
Topsoil depth	The thickness of the topsoil from the soil surface to the top of the subsoil. Topsoil thickness is an indication of soil loss through erosion or an indication of compaction which limits rainfall infiltration leading to poor root growth and increased flood risk. Loss of peat thickness is indicative of increased oxidation of organic carbon.
Visual Evaluation of Soil Structure (VESS)	Visual Evaluation of Soil Structure (VESS) Indicative of the quality of soil structure.

Von Post	A classification of the degree of the decomposition of organic matter in soils: Amorphous, semi fibrous, fibrous on a scale from 1 (undecomposed) to 10 (completely decomposed).
Water retention characteristics	Water retention characteristics are a measure of soil water held in the soil at are differing levels of water matric potential (or suction), typically from field capacity (variously taken as 5 to 105 – 33kPa in the UK) to permanent wilting point (1500kPa) at which point water is no longer extractable by plants. Soil texture influences water retention particularly at greater potentials, as does bulk density, with data offering the potential to assess pore size distribution.
Weathering	The process by which materials are broken down into smaller parts and ultimately their constituents. An example is 'freeze thaw' expansion and cracking. There are physical, chemical and biological weathering processes.

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