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REVIEW ARTICLE

# How can soil data and information become actionable knowledge to advance sustainable land management?

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## Abstract

Promoting sustainable land management is key to addressing land degradation but its progress is impeded by the availability and accessibility of the 'right' soil data and information. We focus on government-funded data collection or publicly collected soil data as it is central to effective soil governance. Taking a governance perspective, we discuss what soil information is created and used for, who are the actors involved and how soil information is contributing (or not) to the creation of actionable knowledge. We investigated two countries in depth through a desk-based review and consultation with 40 key informants, collating which soil data and information is collected, analysed, stored, retrieved and used in the UK and Australia. We present a comprehensive overview of public soil databases, including location, year established, stated purpose, current governing institution, accessibility, digital product/s available, cycle of assessment, scale of sampling, soil data presented and depth of soil assessment. The analysis highlights that current shortcomings in soil governance are a result of not adequately valuing legacy soil data and information, and with the loss of human capital, diminished accessibility to soil information leads to disrupted information flows. A critical assessment suggests that available soil information plays a limited role in knowing the soil types of a locality, the condition of soil under various land uses and associated management, which limits its potential for informing sustainable land management. In both countries, there is a mismatch in scale and intention of use for the soil information between the provider and the user: information is currently held at the scale for regional- or nation-level reporting on targets to meet national and international obligations rather than improving soil health or SLM at the farm scale. In addition, available soil data repositories only partially meet accessibility criteria (discoverability, language applicable to audience, open source and interpretative layer for land management implications). We outline steps to improve soil information and knowledge exchange embedded in effective governance arrangements to ensure that soil data and information can become actionable knowledge for SLM. Applying principles and strategies for facilitating knowledge exchange is of particular relevance to this process.

KEYWORDS
inherent and dynamic soil properties, knowledge co-production, knowledge exchange, learning, soil governance, soil health

## 1 | INTRODUCTION

Research and policy have grappled with the question of how to initiate and motivate change to agricultural practices to make food production – and land management more widely – more sustainable. Soil governance is key for achieving such changes. Soil governance refers to the interaction between different societal actors (land managers, government, businesses, interest groups, etc.) to affect change and to align decision-making around soil use and management with societal goals and preferences (Helming et al., 2018). It involves tools and structures such as property rights, institutions and various policy instruments. The crucial role of governance is increasingly recognized to achieve sustainable land management (SLM), regulate usage and address conflict between users, with the implementation of policy identified as a vulnerable area (Ginzky, 2022; Helming et al., 2018). Much emphasis is placed on governments to design effective policies and processes for SLM, but ultimately it is the actions or inactions of individuals that privately own or rent land that affect its sustainability, and governments can only support those actions with direct or indirect incentives (Bartkowski & Bartke, 2018; Montanarella et al., 2016). We acknowledge that governments, agencies, charities and other civil society organizations also own and manage land, but focus here on the management activities of private landowners.

Most productive land globally continues to be vulnerable to land degradation with statistics indicating widespread, continuing land degradation (FAO & ITPS, 2015), compromising the viability of soil for food production. The ability to promote SLM is impeded by three interconnecting issues: (1) the disruption of information flows and loss of human capital amongst those who are the custodians and curators of the soil information, (2) the mismatch created by legacy soil data and information having originally been collected for a different purpose than the current need to evaluate the impact of best management practices or land use change on soil and (3) only a fraction of soil information is readily accessible at a relevant and credible scale for land management (Campbell et al., 2017; Lobry de Bruyn & Andrews, 2016; Prager & McKee, 2015). Thorsøe et al. (2023) also highlight that insufficient communication of existing soil research findings on land management practices to practitioners hinders the adoption of sustainable soil management practices in Europe, and recommended improving access to knowledge to address soil knowledge gaps. An overarching theme of Campbell et al.'s (2017) stakeholder survey was that publicly collected legacy soil data were neither fulfilling stakeholder needs for contemporaneous data at a finer scale resolution to examine trends over time, nor allowing the generation of future scenarios. This gap is further exacerbated by a continued loss of soil expertise and institutional knowledge as people retire or leave the workforce which means that the capacity to gather more contemporaneous data to add value to existing legacy soil data largely remains unaddressed (Lobry de Bruyn et al., 2017, 2022).

The lack of effective soil governance, in particular poor progress in connecting soil information to SLM, is surmised to be further exacerbated because of two contradicting developments. On the one hand, it is increasingly common to see governments divesting direct involvement with land managers and farmers to the private sector, to the effect that significant amounts of data are gathered and held by private businesses. On the other hand, governments and consortiums of research organizations are meant to be custodians of soil information (Ingram et al., 2022; Ingram & Mills, 2019).

Soil governance relies on relevant and sufficient data and information (Weigelt et al., 2015) about the soils, natural environment and the influence that land management actions have on it so that policy instruments can be designed and implemented in a way that reconciles different uses and preferences with ecological processes (Ginzky, 2022; Juerges et al., 2018; Juerges & Hansjürgens, 2018). In addition, soil information can play a crucial role in supporting policymaking and awareness raising (Bouma et al., 2012). This paper collates an overview of the soil data and information that is collected, analysed, stored, retrieved and used in two example countries, the UK and Australia. We then critically assess the role of this soil information in knowing the soil types of a locality, the condition of the soil under various land uses and associated management and its role in informing sustainable land management. We take a governance perspective to discuss what soil information is created and used for, who are the actors involved and how soil information is contributing (or not) to the creation of actionable knowledge (Mach et al., 2020).

## 2 | METHODS, FRAMING AND ANALYTICAL QUESTIONS

The data for this paper were collected via desk-based research, drawing on publicly available databases and repositories, academic literature and grey literature, policy documents and reports in the UK and Australia. Both are developed countries; they share Commonwealth membership and are connected by colonial history. The countries are similar in their public administrative structure (national and devolved nations/states and territories, respectively). Authors' familiarity with soil governance and organizational structures relevant to soil data and command of the language to access and interpret people, material, data repositories and policy documents was also considered in the selection of countries.

In addition to desk-based research, a wide range of actors with soil-relevant knowledge were consulted. Discussions were conducted in person from June to August 2023 with those people representing institutions responsible for the soil archives and soil information of England, Wales and Scotland in the UK and Queensland and New South Wales in Australia to illustrate the views and knowledge of soil scientists, social scientists, farm advisors and policy advisors. Key questions guiding the desk-based research and the consultation with experts are summarized in Table 1. After in-person meetings, there were also follow-up exchanges by Zoom to clarify original discussions.

The extent to which soil data and information are collected and curated is an indicator of the importance that society and respective governments attribute to the nation's soils because these efforts come at a cost. Particularly in times of austerity, governments find it difficult to justify such spending, and without a department or individuals championing the cause of soil, this area will be neglected. Framing is particularly important, and the rise in attention to specific issues such as peatland restoration or soil carbon in the context of the climate change agenda can impact soil governance profoundly.

Accessibility is a crucial aspect: to what extent is soil information accessible and connected to an audience? We posit that there is a mismatch in scale and intention of use for the information between the provider and the user: information is currently held at the scale for regional- or nation-level reporting on targets to meet national and international obligations and much less about improving soil health or SLM at the farm scale. In addition, data custodians may have a preference for their data being accessed via a web portal or digital app, which may not be widely accessible for users, especially those who are less digitally literate or not familiar with soil naming conventions. In addition, such organizations rely on digitally constructed maps from legacy data sets to compensate for the reduction in investment in 'new' data collection or placement of human resources 'on the ground', and the modelled data are rarely verified by further field sampling.

After setting out the respective policy environment, we present information for both countries about the purpose, extent and curation of soil information under two

**TABLE 1** Questions posed to assess current soil data and information.

| | |
|---|---|
| What purpose was the soil data collected for, and has this purpose changed? | • What is the stated purpose of soil information?<br>• Who originally collected these data?<br>• What is the current governing organization? |
| What is the scale and type of soil data collected and how accessible is it to the public? | • What soil data are held and by whom?<br>• How can soil data and information be accessed (website, app) and by whom?<br>• Can users download, analyse and/ or manipulate data?<br>• What is the cost associated with using the data?<br>• What are the digital products produced?<br>• *How much* (*often*) *can soil data and information be accessed* (e.g. *limited number of downloads*)? |
| How could soil information contribute to actionable knowledge for SLM? | • To what extent can privately collected data (e.g. via soil testing) be integrated into public databases?<br>• Is any soil data and information collected via citizen science approaches?<br>• *Is the existence and usage of soil data and information promoted and advertised, where and how?* |

*Note*: *Text in italics* denotes questions that are important to ask, but we have not been able to answer them in the scope of this work.

categories ('Soil mapping and applications' and 'National Inventory of Soil Condition'). This allows us to derive insight into gaps and suggestions for improving soil governance so that soil information reaches its intended audience and advances sustainable land management by creating actionable knowledge.

Table 2 summarizes the public soil databases for the countries investigated. The data presented cover the: location, year established, stated purpose, current governing institution, accessibility, digital product/s available, cycle of assessment, scale of sampling, soil data presented and depth of soil assessment. Empty cells denote that the respective information could not be sourced or are in the planning stage. The full Table 2 is in Table S1. A summarized version with a qualitative assessment of each criterion is colour coded as achieved (green) or not (brown), with the greater saturation of green or brown indicating the greater or lesser level of achievement, respectively. For data accessibility, four criteria were included (discoverability, language applicable to the audience, open source and interpretative layer for land management implications). The levels refer to criteria met as follows: very low level of achievement = zero criteria fulfilled, low level of achievement = one criterion fulfilled, medium level = two to three criteria fulfilled and high level = all four criteria fulfilled.

## 3 | BACKGROUND TO POLICY ENVIRONMENT, SOIL DATA AND INFORMATION IN THE UK

### 3.1 | Policy environment

It is worth noting that competencies and responsibilities for environmental management (including soil and peatland), as well as land use and associated sectors (agriculture, forestry, food and drink), are devolved to the four nations in the UK. In the case of England, the Government's 25-Year Environment Plan (Defra, 2018) recognized both the importance of soil and the need to be able to better measure and understand soil health. The Plan's associated Outcome Indicator Framework (Defra, 2021) proposes to include an indicator on 'healthy soils' by 2024. The Environmental Improvement Plan (EIP) (Defra, 2023a), is the first revision to the 25-Year Plan and is due in 2028. It reiterates the importance of soil and how this vital natural resource will be managed. The EIP states that, by 2028, at least 40% of England's agricultural soil will be managed sustainably, and the area is to increase to 60% by 2030. The EIP also commits to several factors that will establish comprehensive baseline data including 'establish a soil health indicator under the 25 Year Environment Plan Outcome Indicator Framework'. The State of the Environment: Soil report (Environment Agency 2021) highlighted the importance of soil and the need for a greater ability to monitor and report on soil health recognizing that 'There are insufficient data on the health of our soils'. This need was restated in the EFRA Committee Inquiry into Soil Health (EFRAC, 2023). A small survey ($n = 189$ people) conducted during the Soil Health Inquiry found that half of the survey respondents stated that a difficulty encountered when making or contemplating changes was a drop in production and 46% suggested a lack of or confusing guidance. The Sustainable Farming Incentive (SFI), rolled out since 2023, also focuses on soil improvement through practice change. Under SFI, farmers' actions are subsidized so those enrolled can develop a soil management plan, carry out a soil assessment and report on soil organic matter (SOM) levels. However, they will be paid regardless based on the assumption that the actions are undertaken and evidence may be asked for.

The Scottish Soil Framework was established in 2009 to raise awareness of sustainable soil management and encourage greater policy integration. The framework set in motion a process to identify future activities and develop them jointly with key delivery partners (McKee, 2018). A Soil Monitoring Action Plan and Implementation Plan were released in 2012 and 2013, respectively, with the aim to support soil data collection and make 'appropriate data and information available to a range of users' (SEPA, 2024). However, limited funding restricted the implementation of these plans in full, with only some pieces of work taken forward, for example, SEPA's catchment work that included recording evidence of soil erosion. There are no further formal reports on this work to date. A recent review of existing Scottish soil data found that although there was extensive soil information already captured, much of these data were not appropriate for monitoring change in Scottish soils (Neilson et al., 2020).

The recent development of specific soil policy in Wales, for example, the Soils Policy Statement was in its 1st iteration co-produced with the Welsh government policy team. It embedded academic soil scientists over a 18-month period, adhering to a set of design principles to ensure rigour, transparency, inclusivity and accessibility in the evidence review that would underpin the Soil Policy Statement and ensure it was relevant and achievable (Sánchez-García et al., 2023). Wales features as one of the best practice examples for effective soil governance (Peake & Robb, 2022). However, even for 'standard bearer' countries such as Wales, they conclude that they 'still have a long way to go in terms of soil monitoring and reporting'.

### 3.2 | Soil mapping and applications

Across England, Wales and Scotland soil mapping can be dated back to 1947 when work commenced to provide a complete picture of the soil resources of the three countries. Mapping at 1:25,000 scale, almost half the land was covered when, in 1979, the survey received instructions, together with the Scottish survey, to complete respective national maps at 1:250,000, which were published in the early 1980s. Digitization of these maps occurred firstly by scanning to produce a digital dataset that could be manipulated within Geographical Information Systems and has been ongoing since the 1980s. Availability and general use of spatial technology in web and mobile applications allow more soil data to be published, but it needs to be recognized that the initial data were collected over some 60 years. For Scotland, soil data are freely available and searchable through Scotland's Environment Web (https://soils.environment.gov.scot/). The James Hutton Institute in Scotland has taken the original data and created a number of soil apps for use on tablets or mobile devices: Soil Finder and SOCiT. Soil Finder has a number of soil data layers embedded with the polygons of soil types and searchable data points where the various data layers can be graphed for the average value of the soil type (Table 2). For England and Wales, the soil map of the region is hosted by Cranfield University in LandIS (Land and Information System), and access to detailed soil information is made available through a fee-for-service arrangement, but with an academic institutional email, it can be sourced without a fee. The licence arrangement between Cranfield University and Defra UK was introduced in 2017. Soilscapes (https://www.landis.org.uk/soilscapes/about.cfm) is a freely available resource that offers soil overview information at a relatively basic level, with soil described only in qualitative terms and graphics.

### 3.3 | National Soil Inventory of soil condition (NSI)

The recent publication of the Soil Health Inquiry (EFRAC, 2023) raised the shift in focus on the soil as a public good, but also that the data collected historically to determine land capability and characterize the soil types of a region through soil mapping were not suitable for a soil monitoring programme. In England and Wales, the National Soil Inventory (NSI) data are located in LandIS.org.uk and licenced to Cranfield University. Based on a systematic grid across England and Wales, spaced at 5 km grid intervals, the NSI data were originally sampled in the early 1980s by the Soil Survey of England and Wales, as it was then called, and it includes information on erosion, land use and lithological information as well as a very detailed soil description including stone abundance, root descriptions and soil horizon boundary information. In 1995, about one-third of the original 1 $km^2$ areas were resampled. Thematic maps for single soil properties were developed for England and Wales based on modelled NSI data for soil carbon, soil pH, Phosphorus and Nitrogen, but also only of surface soil (0–15 cm), and there was no subsequent resampling of original sites.

Preceding the NSI in England and Wales, the National Soil Inventory for Scotland (NSIS1) dataset (1978–1988) was collected using sampling points arranged as a 10 km grid with 721 sites. A wide range of attributes are described, measured and analysed for each site. These range from contextual information describing the surrounding landscape (such as slope and vegetation), down to detailed chemical analyses of each horizon within the soil profile. In addition, a quarter of the original coverage was sampled in 2007–2009 (NSIS2). The original data were published but not the newest round of data collection. Soil data are open source and available in a series of maps based on point data, themes, risks and soil types (Table 1). More recently, since 2022, pilot studies have been carried out to identify potential soil indicators to determine the vulnerability of soils to climate change and how these relate to specific land uses, as well as the James Hutton Institute framing how several programmes will be linked to build a national soil monitoring framework.

The Countryside Survey (CS) led by the UK Centre for Ecology and Hydrology commenced in 1978, and its network covers England, Scotland and Wales (Table 2). Their network of sites across the UK has captured data on the state and change in soil but only from the surface soil (0–15 cm), hence it is unable to show the functionality of the full soil profile and whether sub-soil constraints are present. Despite the number of variables increasing over time from soil organic matter and pH in 1978, to nutrients, contaminants and biodiversity indicators in 1998, and soil physical measurements and biogeochemical fluxes in the latest survey in 2007, the number of soil properties is still limited (Emmett et al., 2008). In a recent publication based on CS data, there were four soil properties examined: bulk density, soil organic carbon (SOC, can be calculated from soil organic matter [SOM] = C*1.72), soil pH and earthworms (Feeney et al., 2023). A new initiative called the England Ecosystem Survey (EES) is planning to expand the level of soil data to 24 soil properties and survey 2500 sampling points for soil monitoring over 5 years (Table 2) (Sloman et al., 2024). The methodology has some similarities to the CS, but will not be resampling CS locations whose exact sampling points remain confidential.

**TABLE 2** Highlights of soil information repositories in UK and Australia in terms of achievements in accessibility, digital products, cycle of assessment, scale of collection and display, type of soil data and depth of soil assessment for informing SLM.

| Location | Year established | Stated purpose | Products available | Current governing institution | Accessability (high, medium, low, very low) | Digital products compiled from past data collections |
|---|---|---|---|---|---|---|
| England and Wales | 1947 | *National Soil Archive*: The purpose of effectively communicating a general understanding of the variations which occur between soil types, and how soils affect the environment. Soil heavily influences our whole ecosystem and is a fragile resource that needs to be understood and protected | Soil-landscape maps from LandIS, Digitized and available through Soilscapes viewer (2011) | Cranfield University | Low | Yes |
| England and Wales | Early 1980s | *National Soil Inventory*: Collectively, NSI data are statistically representative of England and Wales soils and they offer a valuable foundation for future monitoring of soil quality | Digital soil property maps with Soil Site reporter | Cranfield University | Low | Yes |
| England | 2023 | *England Ecosystem Survey*: Data on ecosystems and landscape is often of variable quality, expensive to collect, difficult to access, and out of date. In order to make informed environmental decisions, government and other organisations require better data, and this is what England Ecosystem Survey has been set up to provide. EES differs from other surveys not just in its scale but also in the wide range of landscape types it covers, from protected sites and priority habitats to farmland and urban-edge habitats. It will let us draw comparisons between these land use types | Baseline map of soil health by 2028 | Natural England (DEFRA) | Unknown | Planned |
| England | 2006 (in UK) | *BioSoil*: Is a demonstration project, part of the programme of the International Cooperative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests). This project was a test for the development of operational soil monitoring at a large scale | Digital soil property maps available through UK Soil Observatory (UKSO) | Forestry Research | Low | Yes |

| Repeated sampling of orginal location | Contemporary data being collected from original locations | Cycle of assessment | Scale (national, regional, local) | Soil type or association | Soil physical properties (number[a]) | Soil chemical properties (number[a]) | Soil biological properties (number[a]) | Soil depth characterisation (full profile, 0–30/40 cm, shallow (0–15 cm)) |
|---|---|---|---|---|---|---|---|---|
| Not applicable | Not applicable | Legacy data collected from 1947 to 1979 | National, regional | Yes | Yes (2) | Yes (1) | No | Full soil profile |
| Yes | No | Original data collected early 1980s, data collected from one third of original sites in mid-1990s. | National, regional | Yes | Yes (2) | Yes (21) | No | Shallow soil surface |
| Planned | Yes with a common sampling protocol but a different set of soil variables to other Soil monitoring programs | Over a five-year cycle a survey of at least 2500 1-km$^2$ squares, with ecological surveyors spending up to a week at a time in each one. In each square they record information on plants, habitats, hedgerows, streams and rivers, trees outside of woodlands, ponds, landscape, and soils | National, regional | Unknown | Yes | Yes | Yes (3) | 3 depth increments to 40 cm |
| Unknown | No | Soil resampling of a number of the Level II sites has been carried out during 2016–2017 | National, Regional | Yes | Yes | Yes | No | 4 depth increments to 40 cm |

(Continues)

TABLE 2 (Continued)

| Location | Year established | Stated purpose | Products available | Current governing institution | Accessability (high, medium, low, very low) | Digital products compiled from past data collections |
|---|---|---|---|---|---|---|
| Scotland | 1930s | *National Soil Archive*: This is a hugely valuable national resource – each sample is a time capsule which gives us an insight into past soil conditions and, by comparing them with samples from today, we can find out how these have changed | This information has been summarised into the Scottish Soils Knowledge and Information Base (SSKIB) which can be accessed through the SoilFinder website. SoilFinder was previously named SIFSS. Also accessible through UKSO, and redirected | James Hutton Institute | Medium | Yes |
| Scotland | 1978 | *National Soil Inventory*: The most recent State of Scotland's Soil Report was published in 2011. It collated the information available at the time from a variety of sources. It looked at the benefits soils provide, the processes that damage soils and the effects that damaged soils can have on people, the economy and the wider environment | Web map service via: https://map.environment.gov.scot/Soil_maps/?layer=11 with a variety of maps of Soil, Capability and Thematic soil properties (topsoil organic carbon, available water capacity, soil texture in nitrate vulnerable zones, carbon and peatland, soil phosphorus sorption capacity), Point data and Risk maps of selected soil properties. Only a single layer can be viewed at a time | James Hutton Institute | Medium | Yes |
| Northern Ireland | 1980s | *Countryside Survey*: This current planned survey forms part of the monitoring and evaluation of the Environmental Farming Scheme and will also help inform a range of policy development and reporting obligations relating to the environment | | Department of Agriculture, Environment and Rural Affairs (DAERA) contracted to the UK Centre for Ecology and Hydrology, in collaboration with the Agri-food and Biosciences Institute and Queens University Belfast | Low | No |

| Repeated sampling of orginal location | Contemporary data being collected from original locations | Cycle of assessment | Scale (national, regional, local) | Soil type or association | Soil physical properties (number[a]) | Soil chemical properties (number[a]) | Soil biological properties (number[a]) | Soil depth characterisation (full profile, 0–30/40 cm, shallow (0–15 cm)) |
|---|---|---|---|---|---|---|---|---|
| Not applicable | Not applicable | The James Hutton Institute, and its predecessor organisations has been collecting data on Scotland's soils since the 1940s and now has information on over 13,000 locations and over 40,000 individual samples | National, regional | Yes | Yes (1) | Yes | No | Full soil profile |
| Yes | Planned but possibly with a different set of soil variables | 1978–1988, 2007–2009 | National, regional | Yes | Yes | Yes | No | Full soil profile |
| Yes | Yes | 1982–96, 2000, 2007, 2023–2024 | National, regional | Yes | No | No | No | |

(Continues)

**TABLE 2** (Continued)

| Location | Year established | Stated purpose | Products available | Current governing institution | Accessability (high, medium, low, very low) | Digital products compiled from past data collections |
|---|---|---|---|---|---|---|
| England, Wales and Scotland | 1978 | *Countryside Survey*: Monitoring the state and trend of soils is the only way to assess their condition and protect this valuable resource. Caring for soil and the ecosystems they support must rank alongside air, water and biodiversity for maintaining earth's life support systems and our nation's heritage | Digital soil property maps available through UK Soil Observatory (UKSO), SOil funDamentals (SOD) web tool, and Environmental Information Platform for Biological data | UK Centre for Ecology and Hydrology | Medium | Yes |
| England, Wales, Scotland and Northern Ireland | 2020 | *UKSoils*: An understanding of the economic, societal and ecological importance of soil health to support action and research. Ambition is to enable better access to robust, independent information, and provide a space for new proactive communities to share their knowledge and experiences of actions to improve soil health | EU soil observatory, LandIS, SoilGrids and UKSO data and map viewer. **MySOIL** was active until 1 March 2023 | Consortium involving UK centre for Ecology and Hydrology, Sustainable Soils Alliance, University of Sheffield, Earthwatch and SRUC | Unknown | Not applicable |

| Repeated sampling of orginal location | Contemporary data being collected from original locations | Cycle of assessment | Scale (national, regional, local) | Soil type or association | Soil physical properties (number[a]) | Soil chemical properties (number[a]) | Soil biological properties (number[a]) | Soil depth characterisation (full profile, 0–30/40 cm, shallow (0–15 cm)) |
|---|---|---|---|---|---|---|---|---|
| Yes | Yes | Initiated in 1978, and incrementally more samples and soil properties were added in recurrent sampling in 1998 and 2007. The Survey is funded by NERC and a partnership of government funded departments and agencies, headed by the Dept. for Environment, Food and Rural Affairs (Defra). Since 2019, the monitoring has transformed into a NERC funded research platform that utilises an annual rolling program to measure soils and vegetation that will repeat every ~5 years. This makes the program more resilient to annual weather events such as flood and drought | National, regional | | Yes (1) | Yes (6) | Yes (1) | Shallow soil surface |
| Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable |

(Continues)

**TABLE 2** (Continued)

| Location | Year established | Stated purpose | Products available | Current governing institution | Accessability (high, medium, low, very low) | Digital products compiled from past data collections |
|---|---|---|---|---|---|---|
| Australia | ASRIS (1998), ANSIS (2023) | *Australian National Soil information System*: ANSIS has a number of audiences. Policy makers requiring soil data for informed evidence-based decision making. Farmers and farm advisors wanting to use soil data to compare the condition of their soil with a similar soil type. Researchers requiring standardised data on soil properties for research priorities including food security and climate change adaption | ASRIS, ANSIS | CSIRO, Australian Commonwealth Govt with data sharing arrangement with State and territories of Australia | Medium | Yes |
| New South Wales | SALIS (1990s), eSPADE (2012), SoilsNearMe App (2023) | *NSW Soil Data System to the NSW Soil and Land Information System (SALIS)*: By sharing your soil and land information you are contributing to better natural resource management in NSW, and thus a better environment | eSPADE, SoilsNearMe App | Department of Climate Change Energy the Environment and Water | Medium | Yes |
| Queensland | Soil and Land Information (SALI) database (1990s) | To protect Queensland's environment and manage its natural resources, it is necessary to accurately collect, interpret and monitor information about our soil and land resources. This information is used to: assess the variability of soils and landscapes, demonstrate how land use is affected by this variation e.g. agricultural suitability, agricultural land class, and assess land management and land degradation risks | Queensland Globe | Department of Natural Resource Mines and Energy and the Department of Environment and Science | Medium | Yes |

*Note*: Not achieved High; Achievement: High Medium Low V. Low.

[a]Number of soil properties if known.

A more recent development, in 2020, has been the establishment of a harmonized system for the UK which combines soil maps from Scotland, England, Ireland and Wales on both soil types and soil conditions. The United Kingdom Soil Observatory (UKSO) (https://www.ukso.org/quick-links.html) is hosted by the British Geological Survey in recognition of the trends in government data policies and UK soil research activities and can be seen as an effort to promote awareness and usage of soil data and information.

## 4 | BACKGROUND TO POLICY ENVIRONMENT, SOIL DATA AND INFORMATION IN AUSTRALIA

### 4.1 | Policy environment

In Australia, the National Land and Water Resource Audit (NLWRA) (1997–2008) had six objectives which included 'Providing a framework for monitoring Australia's land

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| Repeated sampling of orginal location | Contemporary data being collected from original locations | Cycle of assessment | Scale (national, regional, local) | Soil type or association | Soil physical properties (number[a]) | Soil chemical properties (number[a]) | Soil biological properties (number[a]) | Soil depth characterisation (full profile, 0–30/40 cm, shallow (0–15 cm)) |
|---|---|---|---|---|---|---|---|---|
| Not applicable | Not applicable | Legacy data from the late 1950s to present | National, regional | Yes | Yes | Yes | No | Full soil profile |
| Not applicable | Not applicable | Legacy data from the 1950s to present | National, regional | Yes | Yes | Yes | No | Full soil profile |
| Not applicable | Not applicable | legacy data from the 1950s to present. Soil profile samples held from 1978 as physical specimens by Queensland Govt | National, regional | Yes | Yes | Yes | No | Full soil profile |

and water resources in an ongoing and structured way'. The National Natural Resource Management Monitoring and Evaluation Framework (NM&EF) was established in 2002 by the state, territory and federal governments and approved by the Natural Resource Management Ministerial Council (NRMMC), but the idea first originated from a discussion paper titled *Managing Natural Resources in Rural Australia for a Sustainable Future* (Commonwealth of Australia, 1999). The National Soil Strategy (released in 2021 (DAWE, 2021)) is Australia's first national policy on soil. It sets out how Australia will value, manage and improve its soil for the next 20 years. It has three overarching goals: prioritize soil health, empower soil innovation and stewards, and strengthen soil knowledge and capability. However, the National Soil Strategy came nearly a decade after the Soil Research Development and Extension Strategy was released in 2014 (Commonwealth of Australia, 2014). Although a significant step, this time lag suggests there had been a long period of gestation. Australia, like the UK, has states and territories that govern soil. A central governance body is the National Committee of Soil and Terrain composed of representatives from soil agencies of states and territories governments who liaise with the Federal Government.

### 4.2 | Soil mapping and applications

Kidd et al. (2020) summarized the various stages and states of soil information and data collection periods in Australia. The vanguard of soil survey was led by the Commonwealth Scientific and Industrial Research Organization (CSIRO) from 1946 to 1967, at a scale of 1:63,360 for regional soil maps and analytical data. CSIRO was also involved as the lead agency to design procedures and approaches to systematic soil survey and data collection across Australia, with the Australian Soil Resource Information System (ASRIS) the outcome of the programme, and in collaboration with state and territory agencies. It was last updated in 2014, but a new national portal was launched in 2023 – the Australian National Soil Information System (ANSIS) (https://ansis.net/). Parallel to the national delivery of soil information there are also state and territory governments' soil information systems with various data layers. Each State has electronically stored data, but not every jurisdiction makes it publicly available, and almost certainly in different formats. For example, in New South Wales (NSW), data are freely available through eSPADE (https://www.environment.nsw.gov.au/eSpade2WebApp) on a whole range of data layers, including soil survey maps, land capability, individual soil profiles, and modelled data on soil organic carbon stocks (Table 2). The data that form the maps are primarily sourced from the NSW Soil and Land Information System (SALIS), which was developed in the 1990s. It holds all soil data collected over several decades through government activities and research projects, some even with landholders such as the Healthy Soils for Sustainable Farms (2008–12). Like most soil maps and digital portals of soil data, they are built over decades, and under various programmes but not with necessarily the same intent or purpose. There is a recently released mobile app: Soils Near Me (NSW) in 2023, based on the same data (https://www2.environment.nsw.gov.au/topics/land-and-soil/information/soils-near-me-nsw).

### 4.3 | National Inventory of soil condition

The prominence of soil properties rather than soil type is typical of soil condition monitoring. The federal government with the advent of Regional Organizations in Australia in 2003 established the NM&EF which was principally focused on the impact of a funding programme (NAP and NHT) (NRC, 2004). In the case of soil condition, the national indicators were limited to soil acidification, soil erosion by wind, soil erosion by water and soil carbon content, but there seems only minimal reporting on changes in soil condition. Also, the emphasis was on land degradation types and not on soil health. The current level of data in these various repositories is the outcome of publicly funded government programmes, largely collected from 1990 to 2010, to improve soil and land management by understanding where the most vulnerable soils were, and where soils needed to be protected in the National Land and Resources Audit (NLWRA, 1998–2008) (Lobry de Bruyn et al., 2022). An example of the time-discrete funding of soil data collection on soil organic carbon status was through two federally funded programmes that led to an aptly titled 'Baseline map of soil organic carbon in Australia' (Viscarra Rossel et al., 2014). There currently exists no significant resampling of the original locations, nor the required funding to do so. Regional Organizations have been retained as the governance structure for delivery of regional-based funding of NRM projects, where soil condition still features as an outcome for the 5-year Regional Land Partnerships (2018–2023), detailed as: 'By 2023, there is an increase in awareness and adoption of land management practices that improve and protect the condition of soil, biodiversity and vegetation'. The National Soil Strategy has raised the profile of soil and promised a 20-year commitment to its advancement. In the early phase (2023–2028) (DAFF, 2022), there are four priority actions and the actions related to soil information: Priority 1: Develop a harmonized national approach to the collection, aggregation and analysis of soil information, and Priority 3: Accelerate the adoption of land use and management practices that protect soil and improve soil state and trends. For both of these priorities to become a reality, the expertise to carry out the development is needed. To this end, a National Research, Development and Extension audit of soil science expertise showed a small proportion of people were based in Universities (12%) or extension (6%), while the majority of the survey respondents were in research roles or private enterprise (Department of Agriculture Fisheries and Forestry (DAFF), 2011). Hence the people required to fill these roles are not currently available or being trained in the necessary competencies.

## 5 | SUMMARY OF SOIL INFORMATION ADEQUACY FOR UK AND AUSTRALIA

Exposition of the existing soil information in the form of soil mapping and inventories of soil conditions from the UK and Australia indicates that there were periods of intensive and sustained activity in collecting data (1947–1981 for soil mapping in the UK and Australia; 1978–1990s in the UK and 1997–2008 in Australia, respectively, for soil inventories). The last two decades have witnessed a noticeable consolidation of the earlier data sets but with little indication of advancement in repeating the data collection of soil status from those earlier years (Table 2). Cost-cutting measures and loss of expertise are influencing the ability to maintain a sampling regime (Lobry de Bruyn et al., 2022). Where data collection has been repeated, the sampling effort was also less intense, with suggestions it is inadequate, in some cases, as evidenced by not releasing the latest data sets publicly. Public soil data collection is also subject to funding, and most soil data points have not been revisited to look at trends or impacts of land management on soil properties. Policy initiatives developed through the 2000s have seemingly only recently been actioned, and recurrent government-funding commitments are considered inadequate or ill-conceived, leading to a scaling back of initiatives or reduction in activity or cutting of a programme. The collection of contemporary data for the majority of soil data repositories from the original location is not being undertaken, and in the planning of future soil data collection, any baseline or reference site needs to also be sampled alongside the managed site on the same soil type (Table 2).

Soil data accessibility was generally low or medium as not all four criteria were met by the examined soil data repositories. Low accessibility (60% of databases) was because of a combination of (a) low discoverability, (b) inaccessibility (language too technical, fee for detailed soil data) and (c) missing feedback loop or interpretative layer on the meaning of soil property values or soil type in relation to land management (Table 2). Those soil databases categorized as medium accessibility (40%) were located in a central government portal, open source data with some attempt to connect audiences to the soil information with the use of less technical language. The 'gold' standard is where the user can enter their data and compare it to other local data with guidance on the meaning of the entered value in relation to SLM practices, and none of the examined soil data repositories met that standard (Table 2).

Soil type or soil association was present in all soil data repositories, but the soil classification used was not harmonized with a global soil classification scheme or combined with a less technical language that would be accessible to users with local soil names. Overwhelmingly, the available data are skewed to a few soil properties with greater emphasis on soil texture, soil colour, soil chemical properties and minimal information on soil structure and soil biology (Table 2). Soil data often do not reflect the full soil profile and therefore impediments at depth such as sub-soil acidity and sodicity would remain undetected. Often, preference is given to higher order variables such as land use rather than land management practices, which is likely a consequence of land management data not being documented in detail at each site. A soil management data layer is also not reflected in the soil mapping layers. Hence, causal relationships between soil management and soil condition can only be surmised. The reality of soil surveying random locations on a grid is that not all land use, land management and environmental combinations can be examined.

Scalability of soil information to examine the farm or paddock level is lacking, and most modelled data are not ground-truthed for accuracy, with relevance to regional or national applicability of results (Table 2). To accommodate this, the governing institution may flag caveats, for example, the Scottish Government states that the Soil Finder map was produced at a fixed scale and zooming-in does not change the resolution of the map.

The digital products available are mostly static displays of single soil property maps, and in the case where data can be viewed more dynamically such as Soil Finder or eSPADE, map layers can be switched on and off to be viewed separately or combined over a satellite layer. The use of these digital products is not necessarily evaluated and obtaining feedback from the user is not typically requested.

## 6 | DISCUSSION

Despite governments in the UK and Australia collecting a wide array of soil data and making a share of this accessible to the public, there is not always a clear statement of intent – that is specifying a purpose for the data collection and who is expected to use the resulting soil information (Table 2). At its core, soil data collection is a public investment, but since the target audience and their needs are not fully considered, it is arguable whether the best use is made of this investment. The most common governance failure of soil information is that it is not used for the purpose it was supposedly collected for, such as to 'drive' improved soil management or inform planning and policy. Effort expended on identifying goals and targets and constructing what will be measured is often mismanaged when data gathered are not transformed into information and knowledge that can improve policy design, decision-making and ongoing land management. Monitoring the state of our soils and the impacts of changing land management practices means that data also need to be recollected and in a consistent manner so that data can be compared across time and trends observed.

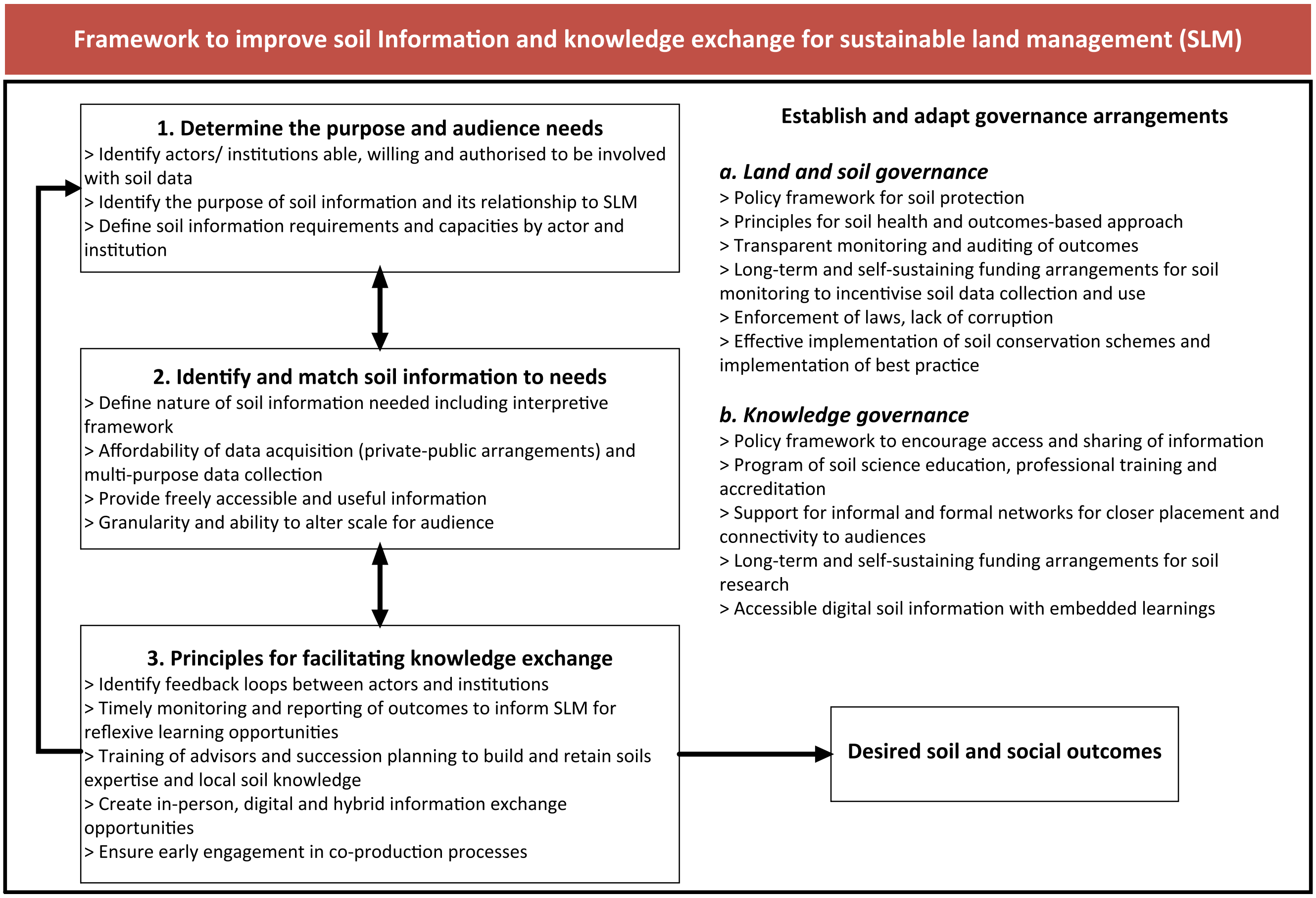


**FIGURE 1** Framework for improving soil information and knowledge exchange for sustainable land management (authors' own construction).

We outline a number of steps to improve soil information and knowledge exchange for sustainable land management (SLM) (Figure 1). Supportive soil and knowledge governance frames the following three steps, as well as the desired outcomes:

1. Determine the purpose of soil information with relevant and compelling arguments to audience/s.
2. Identify the type of soil information that contributes to the desired purpose of SLM.
3. Apply principles and strategies for facilitating knowledge exchange and engagement with audiences to incorporate reflexive learning.

## 6.1 | Establish and adapt soil and knowledge governance arrangements

Appropriate governance arrangements are crucial to facilitate achieving the purpose of soil data collection, matching the soil information to audience needs and ensuring access for the target audience. Governance arrangements interact with and influence the three steps in multiple ways. We distinguish land and soil governance, and knowledge governance. The former concerns the policy framework, legislation and regulations in place for soil protection, and adequate enforcement of this policy (Ginzky, 2022; Helming et al., 2018). Soil monitoring to incentivize soil data collection and use of protocols requires a legislative base and funding arrangements that have longevity and are self-sustaining. Agreed protocols guide data sharing, custodianship, data analysis and updating, data availability and reporting. This can include regulations, codes, standards, labels and certification schemes and stewardship programmes. Monitoring and auditing of outcomes has to occur in a transparent way to ensure stakeholders trust the data and information.

Knowledge governance relies on a policy framework for access to and sharing of information. Peake and Robb (2022) highlighted the importance of establishing programmes for soil science education, professional training and accreditation, as well as support for soil-related research. Ideally, funding arrangements have longevity and are self-sustaining. Both formal and informal networks are needed to support information exchange opportunities, thus building interpretive capacity and reflexive learning opportunities. These networks also serve to contextualize social norms and beliefs to encourage land managers to learn from and make use of soil information for SLM.

## 6.2 | Step 1: Determine the purpose and audience needs

The first consideration before proceeding to the next step is: 'What is the need for a particular set of soil data and information?' This includes determining and clearly articulating the purpose and the respective audience's needs. At this stage, plurality in value propositions needs to be acknowledged to enable shared value creation and capture (Bouma et al., 2011). The two types of soil information considered for the UK and Australia were soil maps and national soil inventories. To ensure soil maps have longevity and sustained value for determining land capability, soil is defined mainly on inherent or stable soil properties that will always limit the soil's potential, and are not likely to be affected by land use change or management over time such as soil profile description and soil texture profile. In contrast, the national soil inventories examined placed greater emphasis on dynamic soil properties, such as soil pH, SOC and soil nutrients that are more likely to be affected by a change in land use or land management. We propose that the two types of data sources (soil maps and soil inventories) need to be considered sequentially: first to locate the soil type (from soil mapping) and second to identify the status of the soil properties for the soil type in question (from soil inventories). Clearly, of greater interest to those actors wanting to understand the productivity and health of the soil is the change in dynamic soil properties, but equally important is the accurate identification of vulnerable or resilient soil types. The need to consider both sources of soil information sequentially is that national soil inventories, in parts of the UK, at least, are not presenting data on the full soil profile, and soil maps from these data were often produced for individual soil properties, without soil type information. This separation of soil information is largely because the soil type remains stable, and the soil's condition is determined by changes in dynamic soil properties.

Current national governments have shifted their priorities to gather data on soil properties that are responsive to land management to strengthen the adoption of SLM practices by farmers and land managers, rather than focus on the soil properties that define a soil type. One such example is soil texture, which has been 'filtered out' owing to its unresponsiveness to land management in recent discussions on suitable soil health indicators that are 'indicative of soil function' (Bagnall et al., 2023; Harris et al., 2023). Ironically soil texture is also a soil property that can permanently limit the potential of soil for certain types of land uses, and defines the soil's vulnerability to a range of pressures such as erosion, soil compaction, salinity and SOC loss. Because this connection is recognized, soil texture is emphasized under Defra's Sustainable Farming Initiative (SFI) 'actions for soils' (Defra, 2023b) in soil assessment and risk management. CFE (Championing the Farmed Environment) also states in a guideline on soil assessment 'Know your soil' and the *only* soil characteristic they use is soil texture (CFE, 2020). It is worth reiterating that the role of soil type and its inherent characteristics are still of value to identify 'at risk' soils to protect them from urbanization or inappropriate agricultural development, and to tailor conservation management or regenerative practices where those soils are likely to be degraded or are already degraded.

While we are not advocating any particular purpose for soil information we are suggesting that energy placed in creating 'new' data sets needs first to consider the value of existing soil information. The salutary lessons of the past have shown that when the collection of 'new' data was proposed and support (funding and expertise) was not committed, it stalled or ceased to progress. Dovetailing historical data sets with new data will acknowledge that knowing your soil is a priority to understanding a soil's vulnerabilities and strengths or the likelihood of change in an evidence-based approach. The overriding purpose of soil information for SLM is for the land manager to learn about the soil's behaviour under stress or management so it can be improved, and develop their own guidelines that are observable and inclusive of local practice and knowledge. The government's need for soil information is sometimes at odds with a locally led approach, and data collection for Governments is more about accountability and reporting on outputs than locally relevant outcomes (Prager & McKee, 2015).

The rationale for the public collection of soil data may also differ from the private reasons farmers collect their own soil data. In Scotland, a recent survey of farmers and crofters showed that of the 73% ($n$=977) that were soil testing, every 4–5 years, the most commonly selected reason/s for soil testing was 'Reduced input costs' and/or 'Targeted use of inorganic fertilisers' (67% each) (Scottish Government, 2022). Soil testing was limited to a small set of soil properties (soil pH, soil phosphate and potassium, SOM, micronutrients), with almost all respondents measuring soil pH and 86% measuring soil phosphate and potassium (Scottish Government, 2022). For England, Briggs & Eclair-Heath (2017) found that the UK farmers mainly soil-tested chemical aspects, rather than more holistic soil health measures. The reasons the authors identified included: little, if any, meaningful guidance for farmers and agronomists regarding the value of soil testing, what to test, when to test, according to what method and how to interpret the test results in light of the particular farm's soil type, topography, weather, crops and rotations.

### 6.3 | Step 2: Identify the type of soil information required for SLM and match to needs

A key question for the second step is 'What is the level of readiness of the soil information systems currently in operation and their ability to fulfil audience needs on SLM at various scales?' We need robust and affordable strategies for sharing data at national, sub-national and farm levels, whether that be online or in-person. The collection and analysis of data is a shared investment responsibility on the part of governments, local and regional authorities, industry-based organizations, private sector information providers and increasingly, land managers. Owing to the inconsistent funding and mismatch between the purpose of collecting soil data and audience needs, past data sets have been viewed as inadequate for future initiatives such as monitoring soil health, with the preference for monitoring more responsive soil properties to reflect soil health improvement. The European Joint Programme for Soil (EJP SOIL, 2020–2025) has stated that 'improving soil knowledge is key to address current and future soil challenges' but was highly critical of how soil information is currently organized and stored with a lack of pan-European standards for soil collection, analysis and mapping and low-quality datasets (Vanino et al., 2023). Soil mapping data that focus on inherent soil properties have fallen out of favour for this role. Although we argued earlier the need to determine the land's potential for certain activities using soil type or land capability maps, inherent soil properties are not regarded as fit-for-purpose to understand contemporaneous soil condition and its relationship to current or previous land management (Bagnall et al., 2023; Harris et al., 2023).

In addition, the scale of the maps produced by the countries reviewed is generally at the regional-landscape level and not at the granularity required for land management at the local level, which would be 1:5000 (Table 2). The digitally produced maps, through a viewer, allow navigation to a locality of interest but as soon as the resolution exceeds the level of data collection, the mapping layer disappears. What is often lacking alongside these visual presentations of soil data is an interpretative layer for soil management or the ability to compare mapped data against other data, such as privately collected data. A further constraint is the fragmented data coverage: the cropping regions of Australia are the least covered, which were classified by the United Nations Food and Agricultural Organization (UN FAO) as having compromised soil health (Biggs et al., 2023; Vanino et al., 2023).

The level of complexity in deciding what type of information is required, its defined purpose and audience relevance can lead to inertia or policy paralysis (Gonzalez Lago et al., 2019). A long period of inactivity despite the urgent calls to document soil condition status or soil health more broadly was observed in the countries examined with no currently active soil monitoring programmes, which has certainly held up documenting soil change (Thorsøe, 2021). Recognition that past NSIs were not assessing soil health status or land management practices on soil health has led to new investments in the UK from 2024 with the England Ecological Survey of Soils across England, and the 'Healthy Soils for a Green Recovery' project in Scotland (Table 2). However, given the long hiatus in measuring soil condition across the UK (the last full Countryside Survey was completed in 2007 and NSI of England and Wales in mid-1990s) and Australia (baseline measures in 1997–2008 only), it is worth considering what is a fit-for-purpose monitoring programme that can fulfil a range of audience requirements and also withstand funding shortfalls or cuts.

One possibility is to link NSI (general and descriptive data) to existing agri-environmental schemes such as in the UK the Nutrient Management Plans (NMP) and England's Sustainable Farming Initiative (SFI) that could provide detailed and site-specific data. Stockdale et al. (2019) advocated for such an approach to the management of soil health in contrast to surveillance monitoring of soil health to account for government investments in SLM. Uptake of NMP has been relatively high in England, with 54%–58% of holdings having an NMP in 2019–2023 (Defra, 2024a). Soil nutrient testing as part of NMP is also high at 70% and soil pH at 74% of those undertaking an NMP. However, the type of soil testing required for an NMP is restricted to available N, P and K, and soil pH, because it is required for ensuring the health of waterways, and not monitoring soil health. The SFI has a programme related to soil testing (SAM1) where the farmer receives a low-level subsidy for a 3-year period to carry out a soil assessment, create a soil management plan and test SOM within the last 5 years for the eligible areas – this is another opportunity to gather locally relevant soil information (Defra, 2024b). Soil assessment in SFI is linked to three separate industry-derived protocols produced by the Agriculture and Horticulture Development Board (AHDB), NIAB and CFE (Defra, 2023b). These soil assessment protocols termed 'voluntary guidelines' by Defra expect the farmer to independently assess the soil from a set of soil properties representing the physical, chemical and biological state of the topsoil (30 cm). Defra should establish user uptake of SAM1 to determine if it could form part of NMP given the latter is well established, and currently lacks soil information on soil structure and soil biology. The understanding of soil and its limits is more easily determined by those soil properties that practitioners can observe, repeatedly, which could also include inherent soil properties or changes in above-ground conditions such as ground cover. It is apparent that privately collected data are not at a high level of mensuration but robust and ground-truthed protocols exist in the UK that are operating independently and are not currently connected with the existing soil data sets held nationally.

Increasingly, the reality that soil sampling, at a local level, is becoming a private investment, with companies using a range of 'soil indicators', but mostly chemical soil properties suggests that consistency in data collection and curation will be challenging. It also remains an open question to what extent the usability of soil data meets the needs of farmers and other stakeholders.

### 6.4 | Step 3: Principles for facilitating knowledge exchange and increasing capacities

The third step involves the application of principles and strategies for facilitating knowledge exchange and capacity building. A recent publication on engagement in nature-based solutions and nature recovery sets out the '9 ingredients' for engagement that strongly resonate with the framework outlined in Figure 1, and the principles that underpin it (Hafferty et al., 2023). Strategies for engagement with audience/s to assess their 'readiness' for using soil information need to balance in-person with online connections to soil knowledge. The two types of connections offer complementarities (Table 3). At the same time, there is an urgency to address the transaction costs and fatigue experienced with in-person engagement by capitalizing on online interactivity potential with 'anywhere and anytime accessibility' (Table 3).

Accessibility of soil information also involves information and digital literacy with an emphasis on non-technical language and low complexity of website navigation to find the area of interest and interpret the data layers. The digital literacy of most land managers needs to be considered and in the case of farmers in Australia and the UK, they are on average in their late 50s, and would not be considered 'digital natives' who have grown up with digital devices, but 'digital immigrants' who may be uncomfortable with digital data and how to use it. A prerequisite to using online soil data is that it is 'discoverable', and once the website is located the user can then navigate to the area they require. In France, farmers rely on their peer group (16%) for information while overall access to other sources of soil knowledge via web pages, printed media or advisory services was lower (10%) (Mason et al., 2023). Once the information was located the majority of stakeholders, which included farmers (37%), stated it was moderately adapted to their needs (49%), but fell short in terms of knowledge exchange (46%) (Mason et al., 2023). A private, bottom-up initiative for soil knowledge sharing is the NSW Soil Knowledge Network (McInnes-Clarke et al., 2019); it works to raise awareness, build trust and add to online sources of soil information.

A pertinent set of questions to pose here is: 'How useful is this type of soil knowledge for a land manager, student, or consultant? How can they use the soil information once it is located?'. The type of information currently available on soil types does not describe their behaviour under certain practices or land uses (often only observable as satellite images). Importantly, soil maps do not embed learnings

**TABLE 3** Pros and cons of engagement opportunities through in-person and online connection to soil information (author's own compilation).

| In-person connections | Online connections |
|---|---|
| • Established social networks required to facilitate in-person engagement<br>• Limited funding to support networks and high transaction costs for support staff<br>• Immediate and direct feedback possible but underused<br>• Forum for sharing experiences and to place realistic expectations on how soil knowledge can inform SLM<br>• Build sense of commitment and shared vision, but difficult to sustain with limited resources<br>• Small reach and attracting individuals already interested<br>• Continuity – follow-up is required to maintain momentum | • Connect dispersed and often unrelated audiences<br>• Require dedicated team of experts to curate, organize soil portals, and respond to queries<br>• Analytics are output-based – likes, time spent on a page, but need to build evidence of engagement impact<br>• Interactive potential with participant's own data and legacy data sets remain under explored<br>• Visual, and can develop functionality for input and display own data against others<br>• Large reach with open access and free (for the most part)<br>• Inclusive in that all people have ability to comment or share their opinion equally |

from soil data to understand the thresholds or tipping points for soil management to either improve soil function or act as an early warning indicator of greater vulnerability to degradation. An examination of private soil collection data in the US and Australia, over a 20-year period, found only a small proportion of farmers were collecting local soil information (25%–30% in a cycle of every 3–5 years), and not intensively or over a large area (Lobry de Bruyn & Andrews, 2016). A farmer rarely systematically retains their soil information, unless it is kept by a private company, and this information is rarely part of any public data repository (Lobry de Bruyn & Andrews, 2016). Similar work in the UK also indicated soil testing for soil health is not widespread and does not inform the adoption of SLM practices (Jaworski et al., 2024). A study across the European Union of 24 countries, including the UK, stated that the adoption of SLM practices ($n = 53$) consisted mainly of early adopters (under 16%), and yet no mention was made of the role soil information in informing practitioners of the benefits accrued with adoption (Heller et al., 2024). The sole reference to soil was that 'clayey soils were said to be hampering factors to adoption of conservation agricultural practices, whereas sandy or loamy soils were perceived as enablers', and only agronomic practices and skills were discussed under 'knowledge', rather than identifying soil improvement through soil testing (Heller et al., 2024).

A federally funded project in Australia (one of 32 nationwide) sought to motivate more farmers to soil test by demonstrating the value of soil testing in identifying soil constraints to production (2022–23). The expectation is that data collected through soil testing will bring with it a much richer understanding of soils and it was proposed to make soil data emanating from the project publicly available. The data will be added to an Australian National Soil Information System – revamped ASRIS (Australian Soil Resources Information System), and for New South Wales is now part of eSPADE and SALIS. The National Soil Strategy (DAWE, 2021) had identified this opportunity and the federal government (Dept of Climate Change, Environment, Energy and Water) was running a pilot programme to pay people for their historical or contemporary soil data, but the government funding for the programme was cut in 2023. Under the SFI in England, the guidelines suggested that the data collected on SOM may be requested to 'help us improve national data on the condition of England's soils' (Defra, 2024b). Our criticism of these approaches is that they are ad hoc and further outsource a government commitment to fund public goods-related data collection, with the expectation that in the future farmers will supply the results of soil testing to support national databases.

Increasing land managers and farmers' adoption of land management practices conducive to improving soil health is now a central plank of soil policy in the UK and Australia for the foreseeable future. The intention to focus communication less on the threats to soil health and the degraded condition of agricultural soils, and instead on how soils can be protected and soil health improved is a major driver, along with the focus on soil as a public good and ecosystem service provider. We believe it is a positive change to the narrative for SLM that is encouraging a desirable outcome of soil management rather than suggesting current soil management is degrading the soil through overuse or inappropriate management actions.

In response to farmers, using soil knowledge for soil health improvement there is also a growing recognition of the importance of local soil knowledge and practice that is often gathered in situ to be integrated into existing soil databases or new ones. A recent study in the UK showed that for farmers, 8 of 11 soil analysis tools involve visual observation with some quantification in situ such as field walking, dig and look, plant root observation, earthworm count, Visual Evaluation of Soil Structure (VESS), infiltration assessment, compaction assessment and slake test, in declining order of use (Jaworski et al., 2024). All three of the soil assessment guides Defra refers to as part of the SFI soil assessment are also highly observational and largely performed in situ using VESS, soil sampling and earthworm counts (Defra, 2023b). Local soil data collected by farmers will provide a more credible approach that is more likely to align with their own practice. Existing soil mapping data can still fulfil a role by assisting landholders in identifying their soil type, and providing an overview of land capability, strengths and vulnerabilities of the soil to land use intensity such as soil erosion, soil compaction or leaching of nutrients. Visual Soil Assessment (VSA) or VESS is already advocated by FAO and industry as a valuable assessment tool and has been demonstrated to be effective with smallholder farmers in Vietnam who have moderate to comprehensive levels of local soil knowledge (Huynh et al., 2022). Of the current soil databases reviewed only the Countryside Survey produced an interactive tool called the SOil funDamentals (SOD) App (released on 5 December 2022) based on data inputs once the user had chosen where the soil is located according to habitat type, soil type (soil texture) and rainfall amount (mm/year) (UK Centre for Ecology and Hydrology, 2022). It then allows the user to input their own data on SOM, earthworm counts, soil pH and bulk density, and graphically compare the entered data to all the values in the database. There is some guidance in plain language about what values are 'good for soil health' but it does not link to practices that could improve SOM, increase earthworm numbers, lower bulk density or obtain an optimal soil pH.

### 6.5 | Desired soil and social outcomes

Improving soil information and knowledge exchange will not only affect soil health but also have social outcomes. Some will be direct results of actions in individual steps, others will be more indirect or only materialize if actions are implemented across several steps. The successful establishment of soil and knowledge governance will determine whether potential outcomes can be achieved. We expect an increased utilization of local soil knowledge, improved information exchange and invigorated social networks that retain sustainable soil management expertise and support the generation of actionable knowledge. Achieving single-, double- and triple-loop learning is a social outcome that can lead to positive behaviour and practice change. The traceability and legitimacy of outcomes will be enhanced. Ultimately, improved soil stewardship will contribute to improved soil health and soil protection.

## 7 | CONCLUSION

The detailed analysis of public soil data repositories in the UK and Australia points to a number of shortcomings that impede effective soil governance. At the core of the discussion is the question of who has responsibility for soil data and information, governments and public bodies, or private businesses and farmers. More societal benefit is associated with accessible public repositories; however, in the long-term soil data and information will have to be a shared responsibility based on private-public collaboration. Ideally, privately collected data should enhance public data repositories (e.g. farmers supply soil testing data to national databases) to ensure data are retained and used more widely to justify the cost of collecting it beyond the seasonal management guidance and compliance with other sectoral policy (such as agri-environment schemes). An important driver will be the enhancement and compatibility of existing online resources. For example, soil maps as visual presentations of soil data should also provide an interpretative layer for soil management or the ability to compare mapped data against other data, such as privately collected data.

Challenges remain in relation to concerns around property rights for privately collected data that may be seen as foregoing competitive advantage, as well as the justification of public spending since online portals of soil information cannot easily demonstrate their impact, especially which type of user they reach and how soil information has ultimately affected SLM. Further challenges are associated with the longevity of programmes and trust in the use of privately collected soil information. Most studies on privately collected soil information have not documented the frequency and extent of soil information collection, meaning it is difficult to forecast the commitment to private soil data collection beyond its presence or absence. Greater thought needs to be given to how soil data for monitoring and documenting soil health is currently collected and scaled while avoiding inertia or policy paralysis as observed in the UK and Australia over the recent decade. Ultimately, if existing data are to have relevance at the local level, it needs to allow entry of local observations and prioritizing ways of soil information collection that fit with landholders' practice and can also relate to existing datasets. As Nikki Baggaley from James Hutton Institute said in a recent meeting on soil health 'we are not starting from scratch and we have potential in existing datasets to contribute to a baseline' (Baggaley, 2024).

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## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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## SUPPORTING INFORMATION

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

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