

Original Articles

Developing a multifunctional indicator framework for soil health

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ABSTRACT

We developed a proof-of-concept indicator framework to monitor soil health based on the delivery of ecosystem services. Instead of distilling soil health to one metric, the framework enables simultaneous comparison of the delivery and trade-offs between different ecosystem services that are delivered by soils, accounting for inherent capability determined by soil type and land use. The framework has potential to explore a whole systems approach, ascertaining soil system response in real time that can detect emergent properties of the system. Initial development of the framework ranked salient soil properties known to be linked and pertinent to the delivery of ecosystem services. These key soil properties, together with other environmental variables were used to create simple conceptual models representing a causal network for soils' contributions to the ecosystem services of climate regulation, food production, water regulation and below-ground biodiversity. The conceptual models were developed into Bayesian Belief Networks populated with relevant national data and expert judgement. The resulting outputs gave an indication of how well (i.e. healthy) a soil can deliver each ecosystem service at a land parcel scale presented in a dashboard app. The output at a specific location can be contextualised or benchmarked against the range of values for areas with similar soil and land use types. The idea was to build the model with readily available data and knowledge but with flexibility for iterative development to refine the framework and models and improve outputs over time. This enables indicator updates using inputs of local knowledge of land management, or when additional soil data becomes available, or when soil policy drivers change, or our understanding of the conceptual and statistical models are improved. The indicator framework can be applied and adapted for use in multiple contexts from reporting national policy targets on soil health to determining soil health for a farmer at the field level.

1. Introduction

Healthy soils contribute to the delivery of multiple ecosystem goods and services, such as food production, climate regulation and maintenance of biodiversity. By delivering these services to society, soils can be related to many of the UN Sustainable Development Goals that drive local, national and international policies (Haygarth and Ritz, 2009; Keesstra et al., 2016; Kibblewhite et al., 2008; Lal et al., 2021). Soil indicators have been developed to assess soil quality (Doran and Parkin, 2015; Karlen and Stott, 2015; Schipper and Sparling, 2000) and have typically focused on specific soil properties, rather than wider soil functions or ecosystem services. Soil health has historically focused on chemical and physical indicators (Corstanje et al., 2017; Lehmann et al., 2020). Although biological indicators have been developed (Nuria et al., 2011; Pulleman et al., 2012; Ritz et al., 2009) they still only typically

constitute < 20 % of indicators in soil health assessment schemes (Lehmann et al., 2020).

Recent focus has been on measuring and monitoring soil health for environmental reporting at a range of spatial and temporal scales, primarily driven by emerging policy directions. At regional scale the EU Soil Strategy for 2030 has the primary objective to have all soils in a healthy condition by 2050. It has proposed a Soil Monitoring Law which aims to make soil health monitoring obligatory for EU member states. In the UK, Soil Health is one of the 66 indicators of environmental change recognised in the 25 Year Environment Plan and the associated Outcome Indicator Framework (Defra, 2023, 2019). Soil health indicators are also required to meet the UK's Environmental Improvement Plan goal of publishing a "baseline map of soil health for England by 2028" (Defra, 2023). From the perspective of an individual landowner or manager, an indication of soil health 'on the ground' is a first step in maintaining or

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enhancing delivery of ecosystem services to society. Several soil health scorecards (Griffiths et al., 2018) or assessments (Hughes et al., 2023; Norris et al., 2020) have been developed for land managers to self-assess and monitor soil health focused on the context of agricultural production (Purakayastha et al., 2019).

There is no overarching framework to monitor soil health that can be applied at different scales and contexts, capitalises on readily available data and is relevant for the requirements of different stakeholders, specifically linking quantitative assessments of soil health to outcomes of interest (Wade et al., 2022). This is because developing meaningful indicators that link soil physical, chemical and biological properties to multiple ecosystem services is challenging (Bünemann et al., 2018; Loveland and Thompson, 2002; Merrington et al., 2006; Ritz et al., 2009). Traditionally, indicators emerge from a set of soil properties (e.g. carbon, pH, nutrients, structure) reporting against benchmarks, thresholds or targets (Feeney et al., 2023; Matson et al., 2024; Nunes et al., 2024), or related to one specific function or ecosystem service (such as food production / crop yield (Matson et al., 2024)) or reporting against indicators of soil degradation (Panagos et al., 2024a). Often there has been a desire to report on a single soil health index, derived from combining, weighting or transforming properties (Fine et al., 2017; Panagos et al., 2024b; Vogel et al., 2019). However, this reductionist approach fails to specifically allow for the assessment of trade-offs in ecosystem delivery by soil, take into account directionality in properties (higher value does not always mean better soil health), the inherent capacity of different soil types to deliver ecosystem services within climate and land use constraints, and the requirements from different stakeholders.

A more comprehensive soil health indicator must acknowledge the complexity of the soil system and the need for this information by a diverse range of audiences interested in soils and their use and management, including government, non-government organisations, land-based industries (e.g. food, agriculture and construction), and the research community. Recent work (Creamer et al., 2022; Rinot et al., 2019) has called for a multi-functional indicator approach, reflecting the complexity of the soil sub-system, rather than distilling soil health to a single number or metric (Wade et al., 2022).

This study proposes a proof-of-concept framework to determine the development of indicators of soil health that reflect multiple ecosystem service delivery. We start with the question: how do soils contribute to the potential delivery of different ecosystem services, given the inherent (and dynamic) constraints of soil type, climate and land use? We present a novel approach from the perspective of delivering multiple ecosystem goods and services at different spatial and temporal scales, moving away from the negative framing of previous assessments focusing on soil degradation (Panagos et al., 2024b) and allowing for the assessment of trade-offs. We sought to develop an approach which incorporated both environmental data and expert knowledge, which was transparent, adaptable and updatable and that allowed users to assess the contribution of soils to the delivery of different ecosystem services at a specific location. The final output is a prototype tool where a user can determine, at a selected location, the probability of different ecosystem service delivery from soils as an indicator of soil health.

2. Methods

Recognising that soil is a complex system (Faybishenko et al., 2016; Phillips, 1998) a starting point was to identify practical lessons learnt from other projects that could be applied to developing indicators of soil health. Two aspects of complexity were considered 1) mathematical; including interacting networks, feedback loops, ordered and disordered behaviour, emergent phenomena and influences of the wider environment and 2) conceptual; including incomplete or uncertain knowledge of the system, difficult to communicate or understand concepts, subjective language interpreted differently by users, and visualisation or reporting challenges of outputs. Considering these two aspects, we

conducted a rapid review of projects that had developed indicators for other complex environmental systems that were currently being used for monitoring policy targets or outcomes. This was augmented with targeted interviews with key Joint Nature Conservation Committee personnel involved in a variety of national (UK) and international indicator projects that captured environmental complexity. The projects covered environmental indicators linked to a variety of directives, legislation and policy such as marine ecosystem and natural capital modelling (EC Marine Strategy Framework Directive; EC Water Framework Directive) and common standard monitoring of statutory sites (EC Habitats Directive; EC Birds Directive, Ramsar, UK Wildlife and Countryside Act). The responses from the review and interviews were used to construct a framework for developing indicators in complex environmental systems from which we could develop indicators for soil health.

We initiated the soil health indicator development through consultation with a steering group comprised of representatives from key UK policy areas (Soil Policy Team, Department of Environment, Food and Rural Affairs) and non-departmental government bodies responsible for measuring and monitoring soils (Environment Agency, Natural England and Forest Research). This initial consultation phase set the definition of soil health in the context of the indicator framework, defined terminologies (e.g. function, attribute, variable, metric), and defined the scope of the proof-of-concept framework to ensure it could align with policy and potential user priorities. Our definition of soil health for the indicator framework was “the ability of soil to perform its functions and to deliver ecosystem goods and services. The range of functions and ecosystem services provided should reflect the different capabilities of different soils – a ‘healthy’ soil is therefore one in which ecosystem services are provided at an acceptable level given inherent underlying constraints and the purpose of the land use”.

Consultation with the steering group continued throughout the development of the proof-of-concept where feedback was elicited on the selection of ecosystem services, soil properties, modelling approaches, visualisation tool and potential use cases for the soil health indicator framework.

2.1. Linking soil properties, functions and ecosystem services

In consultation with the steering group, the ecosystem services selected were based on representing a diverse set of services and those that had significant policy relevance as headline goals in the U.K. 25 year Environment Plan (Defra, 2018). The ecosystem services selected were 1) climate regulation (through soil carbon storage) 2) water regulation (through soils' contribution to runoff reduction) 3) maintenance of biodiversity (through soil biodiversity) and 4) food and fibre production potential (through soils' contribution to land capability for agriculture).

A semi-systematic literature review was conducted of soil properties associated with soil health or aspects of soil health. A combination of bibliographic databases (Web of Knowledge and Scopus), search engines (Google Scholar and Bing), conference proceedings and grey literature sources available to experts within the team, was used to search the scientific and grey literature. Boolean operators ‘AND’ and ‘OR’ were used to combine search terms into text strings to refine the search for specific words in the title, abstract and keyword of articles (Supplementary Table S1).

The literature identified from the review was assessed against a comprehensive ‘logical sieve’ to objectively select, score and rank different soil properties associated with soil health and delivery of ecosystem services (after Corstanje et al., 2017; Ritz et al., 2009). The logical sieve approach has been adopted by others for soil biological indicators (Zwetsloot et al., 2021) but our approach goes further to include a whole suite of soil health indicators using a combination of data driven and expert knowledge approaches. To ensure a robust, repeatable and auditable selection process for candidate properties of soil health, the soil properties were scored against relevance to their 1)

sensitivity to the delivery of soil functions and ecosystem services 2) applicability in different land uses and 3) technical challenge criteria. Technical criteria were based on (Merrington et al., 2006), with additional criteria based on the team's expert opinion related to the scope of the indicator development allowing for a semi-objective way of assessing multiple properties of soil health (Black et al., 2008). The technical challenge criteria against which the soil properties were scored included relevance and significance (to functions and ecosystem services), measurability (in field and laboratory), sensitivity, discrimination and practicability, sound analytical methodology, efficient and cost effective, policy relevance, integrative indicators, geographical coverage (how widespread is the use), availability of threshold or baseline data, ease of comprehension and clarity, complementarity to emerging indicators, and sensitivity to change. Each criteria was scored individually and an aggregate score (sum with weighted functions) was reported for each soil property. For further descriptive detail on the criteria see Supplementary Table S2.

When selecting soil properties that would be fed into models of ecosystem service delivery, it was noted how both dynamic and static soil properties can shape and determine soil health. Dynamic soil properties (e.g. soil organic matter content) can be changed by land management practices (such as tillage or crop rotations), which can be driven by policy interventions. Static soil properties (e.g. soil texture) may not vary over time in response to an intervention in a given location, but provide important context to the constraints to ecosystem service delivery that is possible there (e.g. the capacity of soils to store carbon is greater in clay soil than sandy soil (Johannes et al., 2017; Prout et al., 2021)).

2.2. Developing conceptual and statistical models for ecosystem service provision

A common criticism of assessments of ecological multifunctionality are the lack of explanation of how variables or properties are selected and how they relate to ecosystem functioning or processes (Garland et al., 2021; Manning et al., 2018). We address this shortcoming specifically by applying the logical sieve to identify soil properties that were most pertinent to soil health and associated delivery of ecosystem services. The top ranked soil properties provided the basis for the initial development of conceptual ecological models, although not all the identified soil properties would be relevant to the delivery of all the ecosystem services considered here.

The conceptual models were constructed based on expert knowledge of mechanistic processes and empirical relationships that link environmental variables (here, soil and environmental properties) to ecological processes and the delivery of the ecosystem service. A draft model for each ecosystem service was co-developed in an interactive environment (stormboard.com) and reviewed by the project team, eventually providing consensus on the variables included and links between soil properties, environmental factors and ecological processes within the model. In each model we accounted for the inherent capacity of different soils under different land uses to deliver ecosystem services by including soil type (texture) and land use as nodes within the model.

The conceptual models provided simplified representations of the delivery of ecosystem services by soils, linking soil properties and functions, environmental processes, transformations and response. They were not intended to replace mechanistic models that already exist (e.g. RothC), rather represent the contribution of soils to the delivery of the selected ecosystem service. The conceptual models also offer a framework for estimating ecosystem service delivery where current data scarcity limits the application of mechanistic models.

We developed Bayesian Belief Networks (BBNs), using the R package 'bnlearn' (Scutari, 2010), for the climate regulation and water regulation ecosystem services provided by soils. Resource and data scarcity limited the development of a functioning BBN to represent soils' ability to support biodiversity and food and fibre production potential. A BBN is

a probabilistic graphical model that represents a set of variables and their conditional dependencies using a directed acyclic graph (DAG). BBNs are useful for predicting the likelihood of an event or phenomenon given a set of possible known causes or variables that are represented by nodes and their interactions in a DAG. They are useful when data is scarce or incomplete where there could be greater uncertainty in model predictions. The graphical approach provides transparency in visualising the dependencies between the variables and can facilitate decision-making where action can be taken to change the state of a variable (e.g. by changing soil management practices) to influence the final outcome (e.g. ecosystem service delivery by soil).

The conceptual models were used to develop the DAG by identifying key nodes (soil properties, environment variables and management practices) and their connections representing causal relationships, with the end of the network predicting the likelihood of ecosystem service delivery. Some small adaptations were made to the conceptual models based on data constraints and input formats required for the BBN. For example, in the climate regulation network we removed fertiliser and soil management nodes, as we did not have data representing these nodes. However, operationally we anticipate the land manager would input this data directly in the tool to represent these parameters. Additionally, the crop management was split into separate nodes for each management option so that the causal relationship of each management type could be incorporated into the model.

In this proof of concept, we developed simple node states based on broad categorical variables or numerical ranges. For example, land use was identified by a land use category (e.g. arable, grassland, woodland). Temperature was defined as 'low', 'medium' or 'high', based on the range of average temperatures across England (for full details for each variable state see Supplementary Table S3). The links between the nodes are represented by conditional probabilities, representing the probability of an outcome based on the combination of node states. To parameterise the BBN, we used a random sample of 100,000 25 m grid points to assess node states using spatial data and calculated the conditional probabilities. For nodes where we did not have sufficient data, expert input was used to define the node states and conditional probabilities. The final predicted ecosystem service delivery at a given location was reported as 'low', 'medium' or 'high'.

2.3. Developing a soil health indicator dashboard

Results from the modelling were connected to an R Shiny application so that model outputs could be related to a specific location on a map. This enabled a user to select a location and view the results for delivery of multiple ecosystem services for the selected location at a land parcel scale. There was also an option for the user to input current or potential local management decisions or additional data and view the resulting change in ecosystem service provision.

3. Results

The short literature review and targeted interviews with key personnel involved in a variety of indicator projects identified an iterative and repeated cycle for indicator development was needed; from gathering the evidence, developing models or frameworks, communicating outputs and consultation with users (Fig. 1). The development of the soil health indicator framework followed this approach by taking the process through the first cycle to develop a proof-of-concept that could be subsequently developed through future iterations.

3.1. Ranked soil properties as key soil health indicators

We applied the process framework in Fig. 1 to the development of our proof-of-concept soil health indicators. Key inputs (soil properties) that result in meaningful changes in soil functions, soil health and ecosystem service delivery were identified from the literature review.

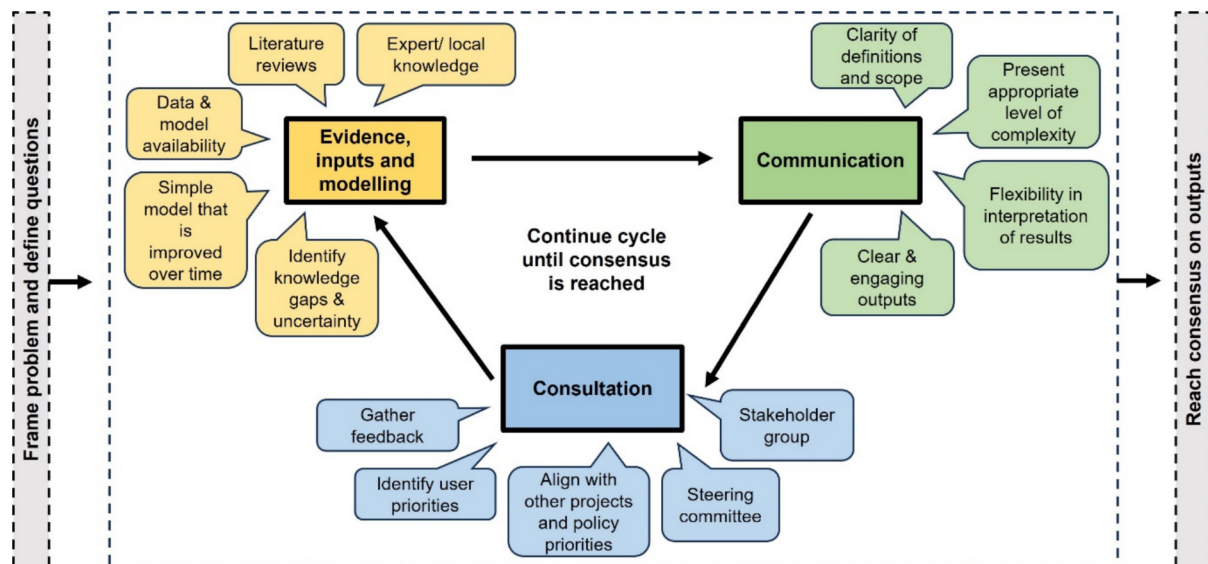


Fig. 1. Processes involved in the iterative development of indicators for complex environmental systems.

The literature review identified 47 peer reviewed papers, 12 technical reports, 3 book chapters and 10 fact sheets/guidance documents for inclusion in the logical sieve. The outcome of the logical sieve identified 47 key soil physical, chemical and biological properties directly relevant for soil health and ecosystem service delivery. The top ranked (upper quartile) scores included a variety of common soil physical, chemical and biological properties (Fig. 2).

3.2. Interactions captured in conceptual models

The conceptual model for climate regulation (Fig. 3) links various environmental properties (rainfall, temperature, land management) and soil properties (soil organic matter, nutrient content, biological activity) that affect soil carbon sequestration, turnover and storage, that are associated with the final delivery of climate regulation. The conceptual model for water regulation (Supplementary Fig. S1) links inherent properties of soil that determine infiltration and water movement, and the generation of surface and subsurface runoff. This network ends with ‘total runoff from soil’ as the indicator of the water regulation function

of soils. For example, a higher value of runoff would be associated with increased flooding risk.

The conceptual model for soil biodiversity (Supplementary Fig. S2) was based on a nested hierarchy of trophic levels, with their interdependencies and feedbacks. The net outcome of these interactions and the various pressures of energy inputs and exogenous molecules impacts the composition and function of the soils’ living components. For example, tillage has a direct negative effect on trophic levels (Fu et al., 2000) which then is reflected directly in biodiversity decline, and the interactions between groups.

The conceptual model for food and fibre production (Supplementary Fig. S3) demonstrates the potential for food and fibre production regulated by soil properties and processes. Key variables such as available nutrients and water are regulated by soil conditions impacting on crop growth and resulting yield.

3.3. Statistical models and outputs

The DAG from the Bayesian Belief Network for climate regulation (Fig. 4) reflected elements from the conceptual model, showing the relationships between and states of the parent and child nodes. For example, inputs of carbon to soils are based on land use, crop management, soil management, temperature and rainfall. When temperature is high (increased crop growth and associated biomass carbon), rainfall normal (low risk of soil carbon loss through soil erosion), crop rotation practiced and crop residues returned to the soil, there is a greater probability that the inputs of carbon to the soil will be high, than when the temperature was low (see excerpt of probability tables in Fig. 4). The final output of the BBN indicated the probability of high, medium or low contribution to climate regulation through soil carbon storage or water regulation through runoff reduction (Supplementary Fig. S4).

The dashboard was developed to display each ecosystem service delivery so that comparisons and trade-offs could be visualised. Rather than reporting the most probable outcome, the probabilities of the ecosystem service delivery of being low, medium and high are reported in the dashboard, so the level of uncertainty can be determined by the user. The dashboard shows simultaneously the delivery of multiple ecosystem services by running the BBN for the node states represented by the location selected (Fig. 5). For each ecosystem service, there are three scenarios reported and represented by each ring in the chart (Fig. 5). This enables the user (in this case a landowner or farmer) to compare or benchmark the outputs against the following contexts 1) the average ecosystem service delivery across England (inner circle) and 2)

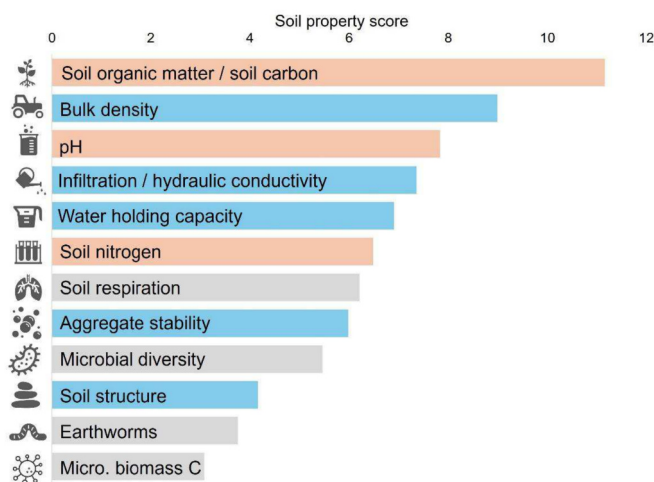


Fig. 2. Soil property relevance and significance to soil health and ecosystem service delivery (scores). Upper quartile of ranked properties shown. Chemical (orange), biological (grey) and physical (blue) soil properties. Micro. Microbial. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

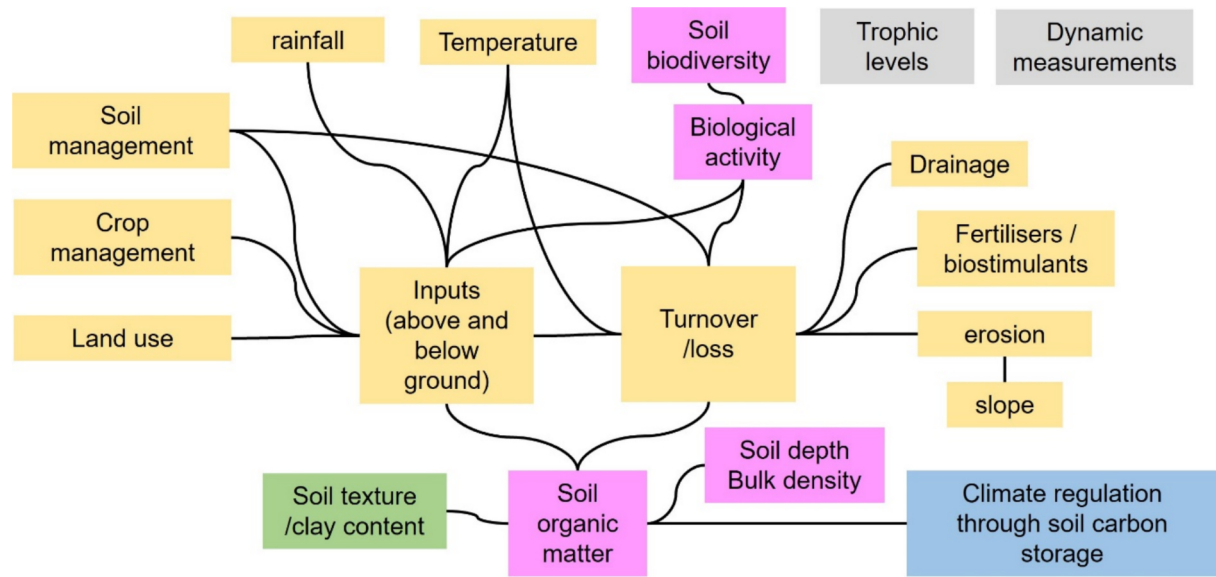


Fig. 3. Conceptual model for soil's contribution to climate regulation. Yellow: environmental variable or process; Green: soil property; Pink: soil property identified from the logical sieve; Blue: Ecosystem Service; Grey: other considerations that currently lack sufficient data. Lines between boxes represent causal relationships e.g. crop management has an impact on above and below ground inputs of organic carbon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

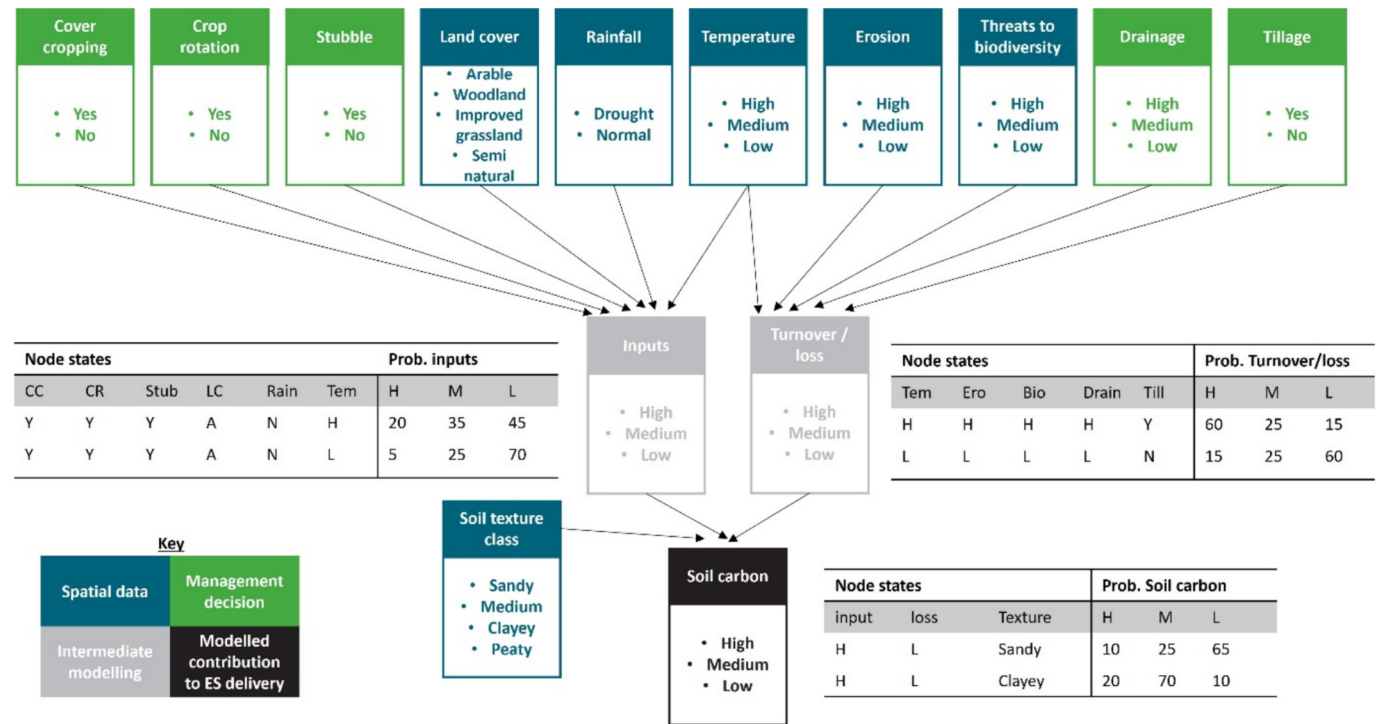


Fig. 4. A directed acyclic graph (DAG) showing the nodes and node states used in the Bayesian Belief Network modelling to determine delivery of the climate regulation ecosystem service (through soil carbon storage). Inputs for the nodes are based on spatial data (blue) or rely on users to input a land management decision via the dashboard (green) to model soils' contribution to the final ecosystem service delivery (black). Table inserts are example excerpts of the full probability (Prob.) tables for inputs, turnover and soil carbon for contrasting node states. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

average for all land parcels of the same soil type and land use as the land parcel selected (middle ring). The outer ring represents the output from the BBN for the land parcel selected on the map, using information on land management or local conditions inputted by the user.

In the example for the selected location (Fig. 5) climate regulation has the highest probability for low and medium outcomes (largest

segments in the outer circle) and the outcome at the selected location is similar to the national baseline and areas with similar soil and land use. Water regulation has the highest probability for a medium outcome (greater certainty for this outcome) with some differences between the selected location and similar sites, as the latter demonstrate greater probability of low and medium outcomes (Fig. 5). This indicates the

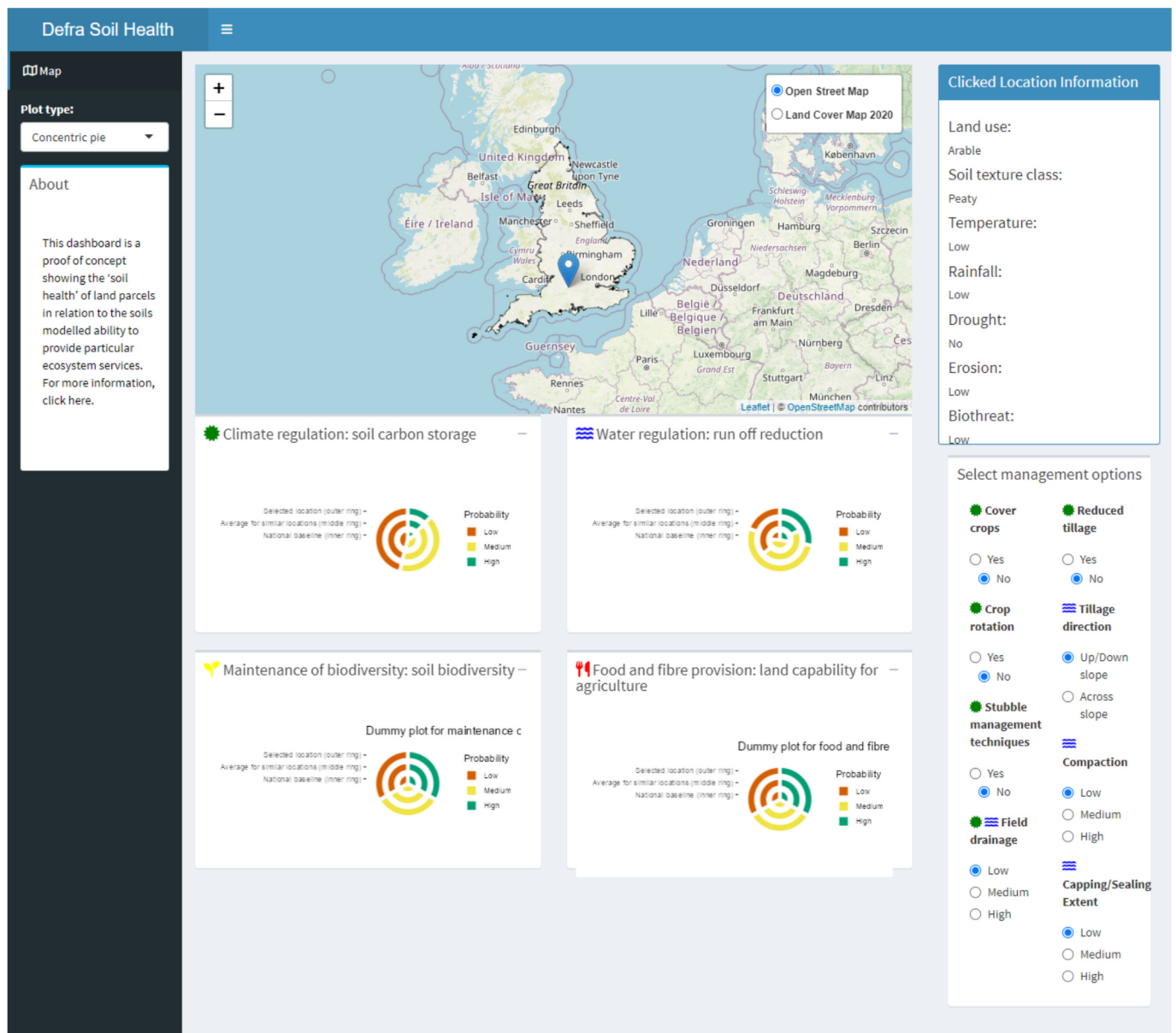


Fig. 5. Proof-of-concept dashboard output for a soil health indicator of ecosystem service delivery. Climate and water regulation are based on outputs from the BBN. Dummy outputs for Biodiversity and Food and Fibre are shown for comparison. The user can enter their own data on local conditions on the right-hand side and the predictions / visual display will be updated. © Open Street Map contributors.

selected location compared to other sites with similar soil or land use has similar outcomes for climate regulation but higher outcomes for water regulation. By changing the management options in the dashboard, the user can also explore the impact of implementing different soil or crop management at the location on the outcomes of ecosystem service delivery.

4. Discussion

4.1. A soil health indicator framework to assess soil multifunctionality

Commonly, soil health is characterised by individual, measurable soil properties such as soil carbon or bulk density or groups of properties, combined by weighting or scoring systems. Often the intended outcome is a universal soil health index (Griffiths et al., 2018) that can reflect the delivery of all ecosystem services (Silva-Olaya et al., 2022). In reality, these approaches are limited in application. It is difficult and

may not be useful to distil soil health into one property, number or index because the result will depend on the desired outcome (i.e. the ecosystem service or goods required). Previous studies have cautioned against using aggregated approaches, such as ecosystem multifunctionality, as these can obscure relationships between communities and key ecosystem processes, leading to incomplete understanding and impacting land management decisions (Bradford et al., 2014). Also, the inherent, variable characteristics of soil over space and time will influence soils' capacity to fulfil ecosystem service delivery. By evaluating the contribution of soils to deliver different ecosystem services, rather than trying to develop a single, universal indicator soil health, one can consider trade-offs. Different actors have different asks of soils and may therefore interpret a single 'health' indicator in different ways. For example, a farmer might consider soils with 'good' health to be those that give the highest possible crop yields (e.g. with high soil nutrient content), whilst a conservationist might consider 'good' health to be soil that supports the greatest range of biodiversity in a particular habitat (e.

g. with low soil nutrient content supports species rich semi-natural grassland). There have been few studies that have addressed explicitly linking quantitative soil health indicators to functional outcomes of interest (Rinot et al., 2019; Wade et al., 2022). Our proposed framework overcomes these shortcomings by linking properties to soil function and service delivery, using a holistic approach focused on multiple ecosystem service outcomes.

4.2. The framework as a method to deepen our understanding of soil function

At present the framework is informed by our current knowledge of the soil system and its functioning. The framework demonstrated here has the potential to test and challenge our current understanding as more granular, accurate and reliable data are integrated into the network through new soil monitoring and sensor networks – providing insight and development of a more complete “systems” model. This contrasts with currently prevailing approaches which may be based only on measurements that are currently available (Lehmann et al., 2020), rather than those optimised to inform a systems-based multifunctional model and understanding (Garland et al., 2021).

The framework can be used to make sense of multiple observations of the system state and dynamics. By reiterating the process (Fig. 1), new observations or connections in the network may arise that are counter to our current understanding and thus have potential to provide new insights into how the soil system responds to pressure and perturbation. This is particularly the case where quasi-real time data can be fed into the model from soil sensor networks linked to a dynamic BBN, which can update outcomes at each time point in the data feed. In these data-rich situations the BBN can learn the network structure directly from the data often revealing new insights about variable interactions and underlying processes, as demonstrated in other systems such as pest infestations and catchment resilience (Adams et al., 2023; Ramazi et al., 2021). For example, climate change impacts on soil multifunctionality have been demonstrated experimentally (Valencia et al., 2018; Wang et al., 2023) a dynamic version of the framework could reveal real-time system response to short-term and long-term perturbations and shocks, providing an early warning system of tipping points in the soil system, where the impact (if any) can be seen across multiple ecosystem services (Carrier-Belleau et al., 2022; Dakos et al., 2019). Questions can be explored on the system response such as what happens to soil carbon turnover in real time in response to climatic perturbations and where do we need to implement additional feedback loops and lags, via soil management interventions, to increase resilience in the system. This proposed proof-of-concept framework can also be used as a structure for developing a new theory of soil health (Harris et al., 2022) where signs of life, form and function can be developed as nodes and outcomes within the network.

4.3. Applications of the framework for national policy/monitoring

A key driver for developing a soil health indicator is the recognition of a global crisis in land degradation and soil health (IPBES, 2018). In Europe, the Soil Monitoring Law (European Commission, 2023) requires member states to monitor of soil condition with a prescriptive list of soil properties, but presently falls short of bringing these together within a comprehensive framework or setting specific targets for soil health. In the UK, there are no specific legislative requirements to measure and report on soil health, however there is a policy driver through the Outcome Indicator Framework to meet a high-level target for “40 % of England’s agricultural soil to be sustainably managed by 2028 through our farming schemes” (Defra, 2023). Our proposed framework provides a mechanism to test progress towards this policy ambition by capitalising on forthcoming soil monitoring data generated through the England Ecosystem Survey that can be used track delivery of ecosystem services. Other use cases include individual landowners who wish to

understand the status of their soils and management required to participate in agri-environment schemes or access private markets where they may be paid for ecosystem service outcomes (carbon sequestration, water regulation, biodiversity enhancement). The framework is intended to be applicable to other contexts beyond the UK as the flexibility in the approach means conceptual models can be adjusted to represent different policy goals or different data sources used to populate the nodes in the networks.

4.4. Next steps

Our proof-of concept-framework includes uncertainty, although this was minimised where possible by incorporating expert knowledge into the models and evaluation by a project steering committee. The idea is to develop soil health indicators using iterative approaches with co-production and consultation with expert and end-user groups, clearly communicating the intended use and uncertainties of the indicator. Where data gaps exist, these could be provided by the user themselves such as a farmer inputting if the field has drainage or if they have used tillage. Simple, on-farm earthworm counts could be utilised in the absence of more sophisticated data on soil faunal trophic levels. However, these observations also contain uncertainties as it is recognised that when monitoring soil management practices, farmer surveys can be biased, with low and unrepresentative response rates (Alskaf et al., 2020).

The soil properties identified in the logical sieve only represent current attributes that are widely used and published. There is potential for the development and incorporation of innovative indicators. In some cases, these are well developed for ecosystem service end-points, for example measuring soil carbon through spectroscopy (proximal or satellite) is well established (Bellon-Maurel and McBratney, 2011; Knox et al., 2015; Nieto et al., 2024). Emerging measurements of soil properties (such as the soil microbiome) may also provide useful indicators of key drivers of soil processes and functions (Lehmann et al., 2020). Monitoring soil fauna can be achieved via ecoacoustics (Robinson et al., 2024) and microbial diversity by high-throughput DNA sequencing (Maron et al., 2018), however before these can be integrated into an indicator framework these metrics will require better interpretability and validation (Fierer et al., 2021).

In its present state, the framework is not sophisticated enough to implement dynamic modelling, but it provides a roadmap to how we could determine the whole system response using dynamic assessments of node states that impact on processes, functions and ecosystem service delivery. Some of these processes and functions could be estimated from existing mechanistic models embedded in the framework (e.g. Roth C for soil carbon dynamics; the ‘CLASSIC’ hydrological model for water regulation (Crooks et al., 2014). In any case, sufficient data is needed at the appropriate scale to run and validate these components of the framework. BBNs are useful when there is data scarcity at the scale needed for the indicator. The ultimate aim is that data or sub-model outputs can replace the expert input in the BBN.

The soil health indicators developed in this proof of concept should be refined further using iterative approaches, based on wider consultation with, and building consensus between expert and end user groups. This should also include identifying crucial data gaps required at different scales (e.g. national to field scale sampling or monitoring). Getting to a framework end point that reports on multiple ecosystem services for different end uses at different scales is not a short-term task: It took 20 years to develop UK indicators for the Water Framework Directive (Environment Agency, pers. comm.).

5. Conclusions

Capturing complexity and function in environmental systems is challenging. In this present study existing frameworks for developing environmental indicators were analysed to build a novel, ‘proof of

concept' approach that represents complex interactions between soil properties and ecosystem goods and services delivered by soils. The approach acknowledges that a universal indicator of soil health is not feasible: separate conceptual models are needed to reflect soils' contributions to delivery of ecosystem services such as climate regulation, water regulation (flood mitigation), food and fibre potential and biodiversity, and as such moves the field of environmental indicators forwards.

The indicator output, in the form of a user-friendly dashboard, can demonstrate to different end uses and audiences how soils can contribute to the delivery of multiple ecosystem goods and services. The approach is flexible and agile and can be updated with new data and new models, which has been impractical, or even impossible, in existing "score card" type approaches (Creamer et al, 2022). It also offers the possibility of providing the building blocks of a "whole system" model for soil sub-systems. It is multi-functional in application, with outputs serving national accounting and auditing, to farmer decision making. Further conceptual development and data inputs are needed to quantify the outputs to give more objective values of soil health.

CRedit authorship contribution statement

Jacqueline A. Hannam: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Maddie Harris:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Lynda Deeks:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Hannah Hoskins:** Writing – review & editing, Project administration, Conceptualization. **James Hutchison:** Software, Methodology, Formal analysis, Data curation. **Amy J. Withers:** Software, Methodology, Formal analysis, Data curation. **James A. Harris:** Writing – review & editing, Conceptualization. **Lawrence Way:** Supervision, Funding acquisition, Conceptualization. **R.Jane R. Rickson:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Jacqueline Hannam reports financial support was provided by United Kingdom Department for Environment Food and Rural Affairs. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.].

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Author contribution statement.

Hannam, J.A. (conceptualization, methodology, analysis, writing original draft, writing review and editing, visualization), Harris, M. (conceptualization, methodology, software, analysis, data curation, writing original draft, writing review and editing, visualization), Deeks, L. (methodology, analysis, writing review and editing), Hoskins, H. (conceptualization, writing review and editing, project administration), Hutchison, J. (methodology, analysis, data curation, software), Withers, A.J. (methodology, analysis, data curation, software), Harris, J.A. (conceptualization, writing review and editing), Way, L. (conceptualization, supervision, funding acquisition) & Rickson, R.J.R

(conceptualization, writing review and editing, supervision)

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2025.113515>.

Data availability

data statement included in manuscript

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Developing a multifunctional indicator framework for soil health

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